Simulation of ballast behaviour under traffic and tamping process

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Simulation of ballast behaviour under traffic and tamping process

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Abstract

The geometry of the railway track is degraded under traffic load, and must be maintained periodically. This degradation is due to the arrangement of ballast particles under loads and vibrations, which results into irreversible plastic settlements. Tamping is a procedure of maintenance, used to restore the correct geometrical position of the ballasted tracks. However, the penetration of the vibrating tines into the ballast causes an increase in the fine particles content by rupture of the edges of the grains and leads to a progressive degradation of the ballast and thus to a loss of its properties.

The goal of this research is a better understanding of ballast degradation and the development of a tool to evaluate the effectiveness of the track tamping, according to the ballast condition and the infrastructure stiffness. This knowledge will make it possible to decrease the destroying effects of tamping over ballast and, consequently, increase the durability of track geometry and ballast.

A two-dimensional finite element model has been developed to simulate the response of ballast under traffic loading and the settlements development. Ballast at different degradation levels is studied. The influence of the subgrade stiffness is also taken in account. Two laws of elastoplastic behaviour are applied: elastic and Hujeux with cyclical plasticity. Both results are presented and compared. A phenomenological model is also developed to analyse separately the effects of traffic loading and track tamping on ballast behaviour and degradation.

This model is supported by full-scale laboratory tests on ballasts and infrastructures of different qualities. Simulated dynamic loading and tamping action are performed. The whole process and the equipment are completely instrumented in order to control and measure several parameters in real time. The evolution of the ballast behaviour is analysed with the measurement of the quasi-static module E, through plate bearing tests performed under sleepers, after each traffic cycle and tamping.

Keywords

Railway ballast – Finite Elements Model – Hujeux elastoplastic law – Plate load test

1. Introduction

Traditionally, almost all the railway lines in the world lie on a ballast layer. Ballast is made of hard rocks, which are crushed in order to make particles of 30 to 50 mm size and which present several rough edges. The main roles of ballast in railways are:

- → resist vertical, lateral and longitudinal forces and retain the track in its right position;
- → transmit uniformly up to the platform the train loads and reduce pressures to acceptable stress levels for the infrastructure;
- → absorb noise and vibrations, especially in high speed lines;
- → provide rainwater drainage and contribute to the elasticity of the railway;
- → facilitate lining operations and correction of geometry defects by the possibility of rearrange ballast particles with tamping.

However, the suppleness of ballast is also a disadvantage: under repeated train loading, the ballast particles rearrange and provoke at a long term a settlement of the track, which is often inhomogeneous. To adjust the track level it's necessary to tamp the ballast every time geometry goes under the intervention limits.

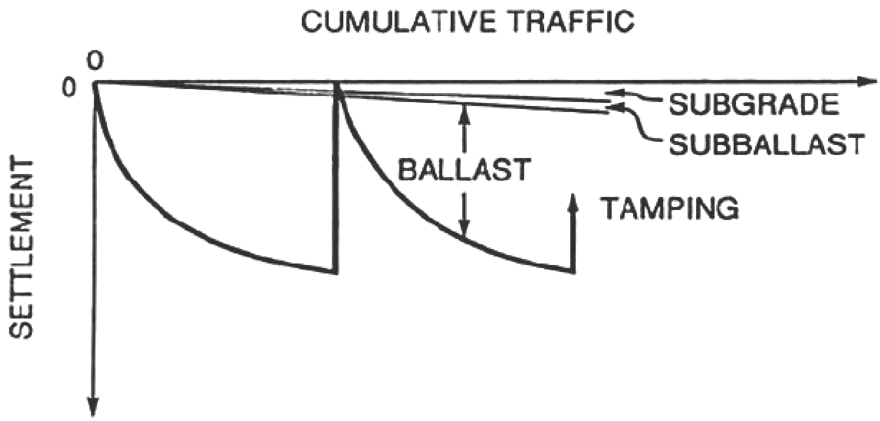
1.1 Geometry maintenance and ballast degradation

Geometry degradation is due to the arrangement of ballast particles under charges and vibrations, which results into irreversible plastic settlements. Tamping is a procedure of maintenance used to restore the correct geometrical position of the ballasted tracks. The track is lifted, while the vibrating tines rearrange ballast particles under the sleeper, restoring the required level. However, the penetration of the vibrating tines into the ballast causes an increase in the fine particles by progressive rupture of the edges of the grains and leads to a progressive loss of the angularity, elasticity and drainage properties (Röthlisberger et al. 2005).

In fact, ballast degradation occurs under track construction, train running and track maintenance (Guldenfels 1995).

This degradation of ballast induces faster settlements in the future, because ballast particle become rounder and their interlocking is not effective. The main consequence is that the interval between two tamping operations decreases (from one every 7 year to twice a year!), along with the long-term effectiveness of the process. This vicious circle can be broken only by ballast renewal.

Figure 1 Evolution of track settlement and its causes



Source: (Selig and Waters 1994)

Ballast and geometry maintenance represent 40 to 50% of the total railway maintenance budget during lifetime. This high investment is due on one side by the frequency of tamping and on the other hand because the work is mainly carried out by night.

1.2 Purpose and approach

The purpose of this PhD project is the comprehension of ballast degradation mechanisms, during repeated train loading and tamping operation. The progressive ballast ageing has an influence on the evolution of track settlements under train loading.

The further goal is the development of a tool of follow-up of the mechanical properties of the railway ballast and infrastructure *in situ*, which can be combined with a railway settlement model, in order to foresee its behaviour and adapt the maintenance to be done.

Once the determinant ballast parameter is identified, a device to follow the ballast mechanic state in situ is developed and performed in LAVOC full-scale test hall.

A FEM model of the track and its infrastructure makes use of these ballast state parameters to simulate the mid-term behaviour of the track under traffic loading and the progressive development of irreversible plastic settlements. Different ballast states are simulated, along with different types of subgrade.

2. Evaluation and follow-up of ballast state *in situ*

We are interested in measuring the in situ state of ballast under the sleeper, where the main loads are transmitted and the highest deformations and stresses appear.

The in situ state of deep ballast is difficult to be measured without a sample extraction. Most of the mechanical parameters, like coarse size, particles shape, friction angle ϕ, Young modulus E, density, empty module e, can only be measured in laboratory.

On the other side, the main non-destructive continuous in situ measurements are geophysics, ultrasound (speed of signal), electric (dielectric constant), radar (GPR) or nuclear ones. However, these measures don't give any quantitative information on the mechanical properties of the material. The electric measures are severely influenced by the superstructure, while the nuclear densimeter is unsafe and not adapted to coarse aggregates. Georadar doesn't give any quantitative result on mechanical properties of ballast and infrastructure, but only qualitative informations.

The selected approach is applying a force and measuring the displacement of ballast with a plate load test. This trial is usually performed on foundations, in order to determine the supporting strength, by applying two loading cycles and one discharge cycle.

According to the Swiss standard SN 670317b (VSS 1998) for ground and infrastructure, a pre-load of 0.01 MN/m^2 is first applied to equilibrate the plate weight. Then the loads applied on ballast are divided in:

→ 7 stages from 0.08 to 0.53 MN/m^2 in the first cycle,

→ 3 stages from 0.53 to 0 MN/m^2 during the unload cycle,

→ 6 stages from 0.08 to 0.45 MN/m^2 in the second cycle.

At each stage, the displacements of the plate are measured. During the two loading cycles, it is possible to obtain the viscoelastic and the plastic strains separately. The formula:

$$E_v = 0{,}75 \cdot \frac{\Delta\sigma_i}{\Delta s_i} \cdot D \qquad [MN/m^2]$$

permits to calculate the two deformation module, E_{v1} and E_{v2}, related to the two loading cycles. They are function of the normal stress applied between two stages and the correspondent displacement difference measured. D is the plate diameter (300 mm).

While E_{v1} is related to the density of ballast in place and its short time behaviour (e.g. loading for some days), E_{v2} is more correlated to the mid-long term behaviour (some years of traffic loading). The link between E_{v2} and the apparent Young module E is expressed by the formula:

$$E = \frac{\pi(1-\nu^2)\cdot E_v}{3}$$

in which ν is Poisson's coefficient. These parameters can be used in further analysis as an input into a FEM model. In this case, the bulk modulus K and shear modulus G are calculated from E and ν with the Lamé formulas for the Hujeux law input needs (see paragraph 3).

2.1 The measuring equipment

A special device allows applying the load directly on the ballast under the sleepers, in the zone where the highest loads are transmitted. The tested sleepers have been pierced in order to insert a rod, which transmits the load to the plate (see Figure 2).

Figure 2 The plate load test device: pierced sleeper, plate and hydraulic actuator

In order to measure the displacements of the plate, a LVDT displacement sensor is fixed to an independently supported beam.

2.2 Test results and conclusions

The load plate test has been performed on ballast before and after tamping operation. The different samples show a high variability on E_{v1} values (9 to 66 MPa), which is reduced for E_{v2} values (43 to 99 MPa).

3. Numerical analysis of the ballasted track behaviour

To study the dynamic behaviour of the railway track on the long term a numerical analysis is undertaken, in parallel with full scale tries in the hall pit.

The objective is the simulation of the full scale tests, in particular the dynamic load of the railway traffic and the consequent mechanical response of the infrastructure. Concerning the ballast bed in particular, the purpose is the evaluation of the geometry degradation rate after every tamping operation, and the trend along with the number of undergone tampings.

3.1 Choice of the model

For the study of the long-term railway behaviour, in a first step a 2D continuous macroscopic finite elements numerical model has been chosen. This model simulates:

- → static and dynamic (cyclic) loading of the structure;
- → interaction between ballast and subgrade layer: stiff (gravel) and soft (silt);
- → settlement of ballast under cyclic traffic loading;
- → ageing of ballast: ballast edges breaking, plasticization.

These phenomena appear gradually, and have effects on a long-term period. For this reason, the model has to be accurate for a long-term analysis of ballast behaviour under cyclical loading. An elastic analysis for the entire structure has been calculated as a reference. Then ballast is updated to an elastoplastic Mohr-Coulomb behaviour law, while the sleeper and infrastructure are elastic. Finally, ballast follows the elastoplastic model described by Hujeux (Aubry and Hujeux 1982; Hujeux 1985). This model implies a multiple hardening and a cyclic plasticity. Three plastic deviatoric deformation mechanisms and an isotropic volume consolidation mechanism are considered. Every deviatoric mechanism is described by two hardening variables: the plastic deviatoric deformation and the plastic volume deformation. The density hardening is common to the four mechanisms, which are coupled. The elastic part of the model is not linear and derivate from a potential. The yield surface of every mechanism is:

$$f_k = q_k - p_k \sin\phi\left(1 - b \cdot \ln\frac{p_k}{p_c}\right) r_k ,$$

Where:

k is the cinematic hardening variable;

q_k *and* p_k are, respectively, the deviatoric variable and the average pressure in the plan k;

p_c is the critical pressure (the isotropic hardening variable),

r_k is the degree of mobilization of the mechanism k.

Depending on the extent of the deformations, it is possible to distinguish three bounded domains: an elastic domain, a hysteretic domain and a mobilized domain.

The model doesn't simulate the tamping process itself, as it's focused on the long-term behaviour of ballast. Tamping is taken in account by its mechanical consequences on ballast, such as the geotechnical plasticization, the breaking of the particles (friction angle decreasing), the compaction (confining pressure increasing), the empties filling (empty index reducing), the pollution (cohesion appearing). The numerical simulation is supported by the parameters measured in laboratory during the real scale tests, such as ballast stiffness, which is measured regularly with the plate load test and its update values represent the ageing during its lifetime.

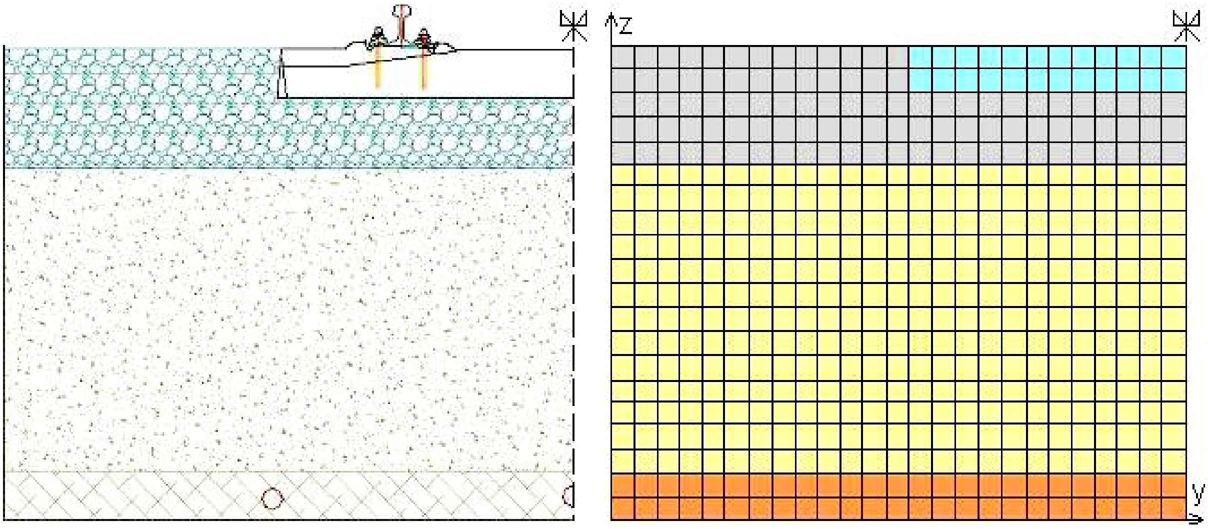
3.2 Choice of the software

To simulate the Hujeux elastoplastic behaviour, the FEM software GEFDYN has been chosen. This academic software was developed at the Ecole Centrale – Paris in 1989 (Modaressi A. 1989). This software is very complete for numerical analysis on geotechnical materials, and can analyse complex problems, such as the dynamic loading, the water level variations in porous media and the effects of temperature. Several behaviour models are possible. The post process software used for the treatment and visualisation of the results is GID.

3.3 Mesh

The structure we decided to analyse is a half railway section, considering the vertical symmetry. It's composed by half monoblock concrete sleeper, a ballast layer, of 30 cm thickness under sleeper, a foundation layer and a base gravel layer. The mesh has been conceived with Z_SOIL, and it consists of 546 nodes and 500 elements, as showed in figure 4:

Figure 3 Creation of the mesh and different layers



The mesh is homogeneous for all the materials. The load is applied on the top edge of 3 linear elements, which is the contact surface between the rail base and the sleeper.

In a first analysis, the sleeper hadn't been included, and the load was directly applied to the ballast. This simplification gave some errors in the results, especially too severe shear stresses in correspondence of the sleeper corner, so a new mesh had to be set.

3.4 Parameters and hypothesis

The analysis is made in continuity of displacements. The calculation is done in two steps: in the first one, the volumetric forces induced by materials weight are applied and the strain state is calculated. In the second step, the previous displacements and strains are reset and the external load (train) is applied to the structure. The sides and the bottom of the structure impede any displacement perpendicular to (against) them.

The half-sleeper and the foundation materials follow an isotropic elastic model. The ballast layer follows a law of elastoplastic Hujeux behaviour. All the materials are supposed dry. The parameters are summarised in the following tables.

Table 1 Ballast parameters for the Hujeux elastoplastic model (NGI 2005)

	Description	Symbol	Typical value
	Density	ρ	1.7 t/m^2
Elastic parameters	Bulk modulus	K	112 MPa
	Shear modulus	G	83 MPa
	Elastic exponent	n	0.38
Plastic parameters	Friction angle	φ	42°
	Compressibility coefficient	β	42
	Dilatancy coefficient	α	1
	Dilatancy angle	ψ	42°
		d	4
Limits of domain	Elastic domain ray	r_{ela}	0.001
	Hysteretic domain ray	r_{hys}	0.03-0.21
	Mobilised domain ray	r_{mbl}	0.8
	Isotropic domain ray	r_{iso}	0.001

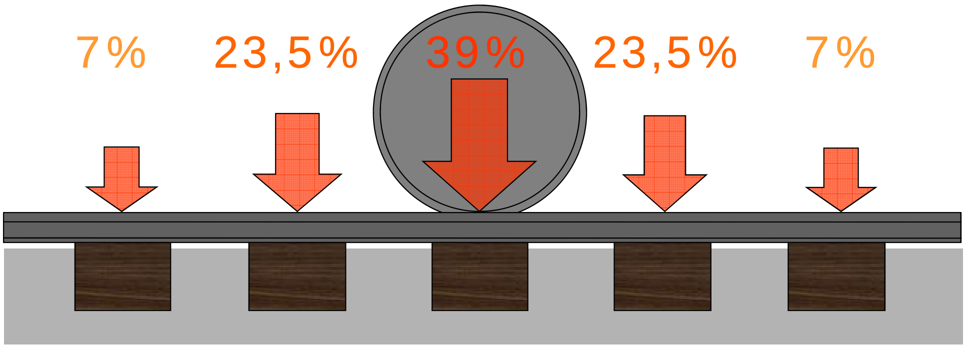
The values of the Young modulus for the gravel and the silty sand have been calculated after measuring the bearing resistance of the two infrastructure materials with the plate load test, in the laboratory full scale structure.

Table 2 Values of chosen the (Mohr-Coulomb) elastic parameters

Parameter	Concrete sleeper	Gravel (subgrade / infrastructure)	Silty sand (infrastructure)
E (Young modulus)	30 GPa	300 MPa	80 MPa
ν (Poisson coefficient)	0.2	0.3	0.35
ϕ (friction angle)	52°	37°	34°
c (cohesion) elasticity	1.00E+16	1.00E+16	1.00E+16
ρ (density)	2.8 t/m^3	1.9 t/m^3	1.7 t/m^3

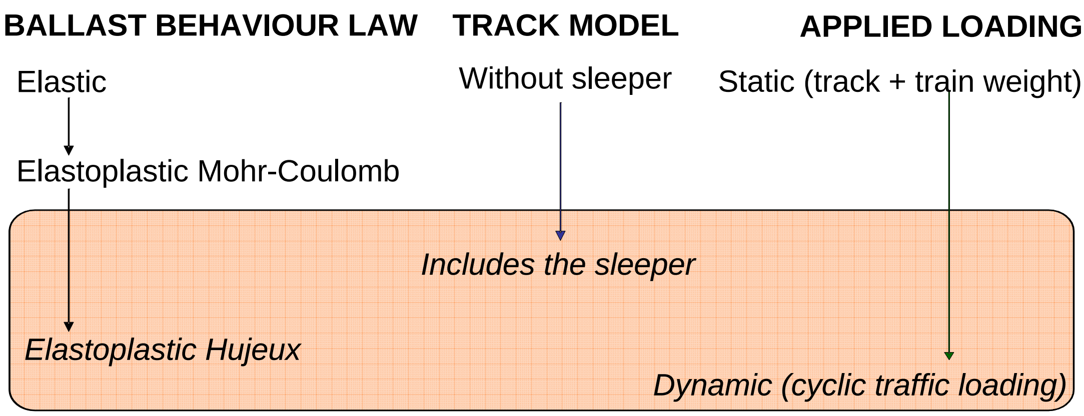
The cohesion has been set to 10^{16}Pa to force the elastic behaviour. The applied load consists of the weight of the rail and a freight train wagon on the most charged sleeper. according to the load distribution over five-sleeper (Profillidis 1984) the loaded sleeper supports 39% the total axle weight, as shown in the following figure. This distribution is due to the distance between the axles, the rail inertial moment and to the gap between the sleepers (normally 0.6m).

Figure 4 Distribution of a wheel load over five sleepers



Hence, the model has been developed step-by-step, as in figure 5:

Figure 5 Implementation of the numerical model



In this paper, we present the results of the simulation on a track model including the sleeper, with the traffic load applied quasi-statically (one cycle). The ballast behaviour follows an elastoplastic model of Hujeux, and it is supposed undegradeded. We compare the effect of two infrastructures of different properties: one is stiff (gravel), while the other is soft (silty sand). The two infrastructure materials follow an elastic behavioural law, as we suppose that they are very dense. The simulated situation is like after a ballast renewal and compaction, on an existing line, with an old infrastructure.

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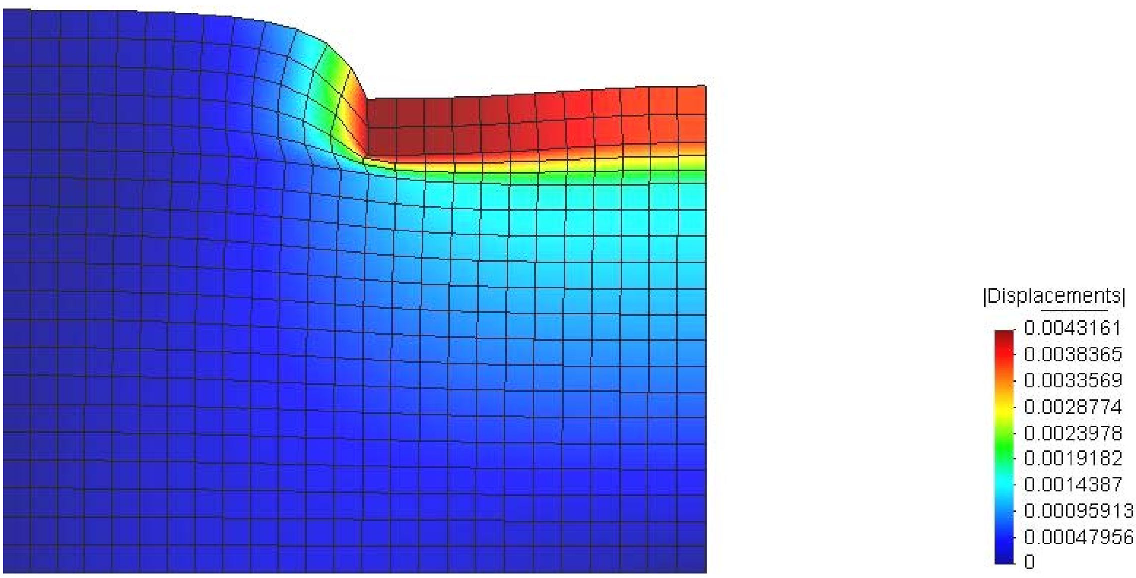
4. Results

4.1 Stiff elastic infrastructure (gravel)

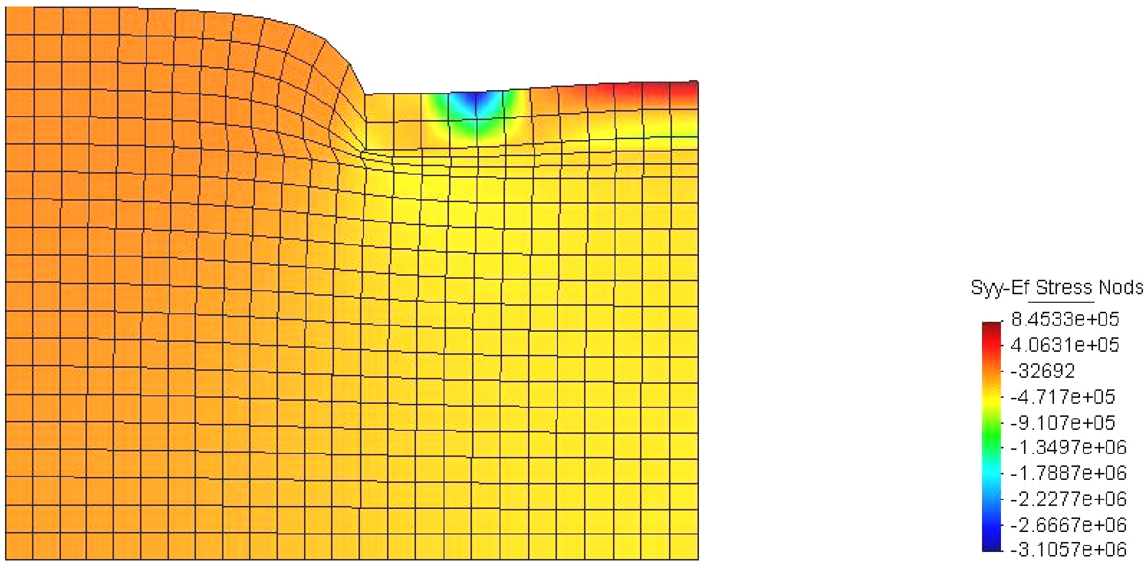
Figure 6 Displacements, stiff + elastic [m]



As we can see in figure 6, the main reason for the sleeper displacement is the progressive deformation of the ballast under the sleeper and, most of all on its low external corner. The maximum displacement occurs on the external sleeper side. The stiff foundation is less concerned by the deformations, which occur mainly on its upper half.

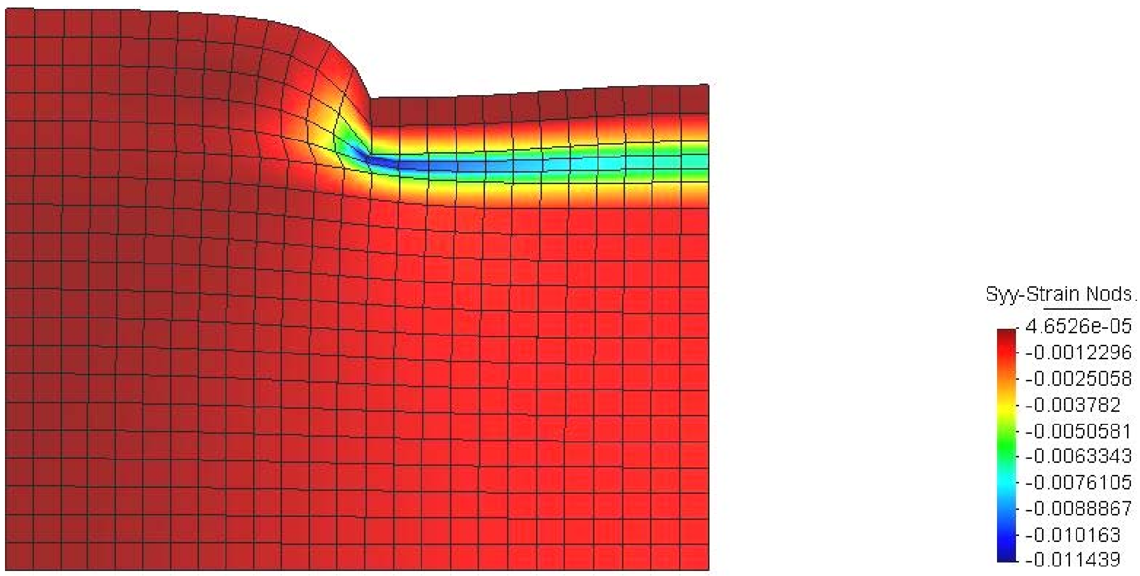
The vertical stresses results, as shown in figure 7, are all concentrated in the sleeper and mostly damped by the stiff concrete. The sleeper diffuses uniformly a share to the ballast bed, which dumps the residual charges by deformation. In the ballast layer and in gravel infrastructure, stresses are in the order of 45 kPa under the sleeper and 30 kPa at the side. Then the stresses are propagated from the ballast to the underling infrastructure layers in a conic form.

Figure 7 Vertical stresses, stiff + elastic [N/m^2]



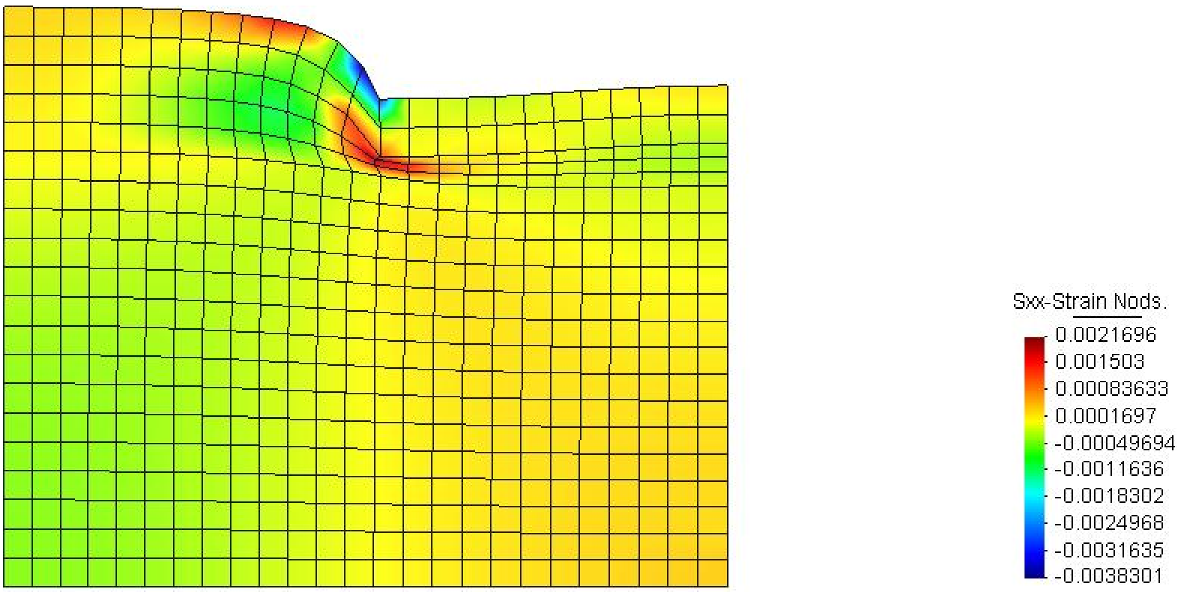
As explained for the displacements, the ballast is the most concerned by the deformations, which are maximal at the ballast top edge (figure 8). A little deformation occurs on the interface between ballast and infrastructure and it's quite constant in the gravel lying under the sleeper. On the external side of the infrastructure and into the sleeper, the strains are very small.

Figure 8 Vertical strains, stiff + elastic



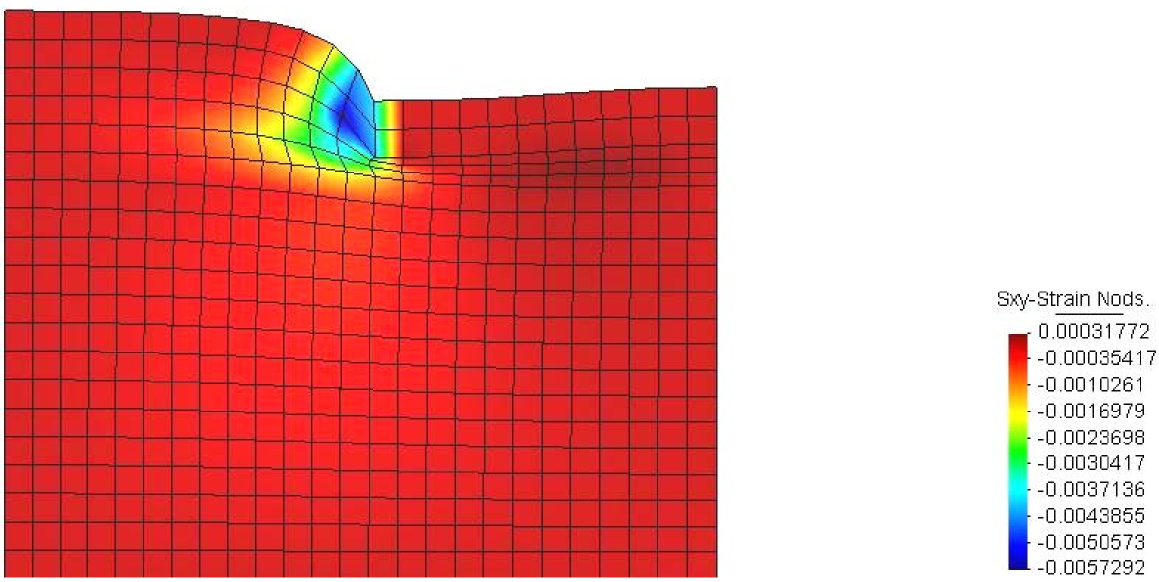
The horizontal strains (figure 9) are low (between -3.8‰ and 2‰) and concentrated in the sleeper side. On the upper edge, the ballast retains the bended sleeper, while at the low edge it tends to get under the sleeper.

Figure 9 Horizontal strains, stiff + elastic



The shear deformations are maximal in the ballast against the sleeper side. Here the horizontal strains are balanced and a clockwise moment is generated at the interface between the sleeper and the side ballast.

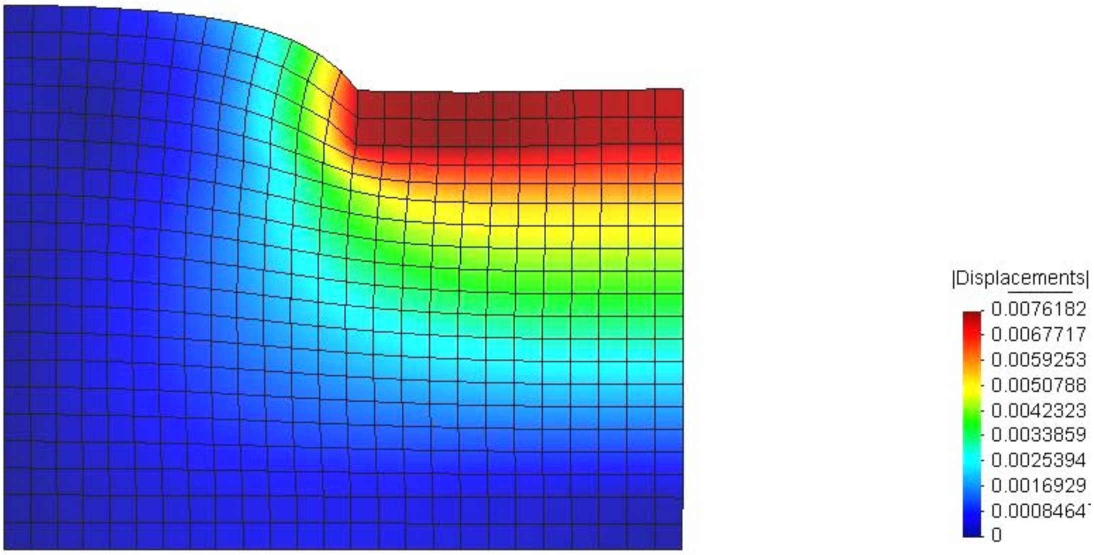
Figure 10 Shear strains, stiff + elastic



4.2 Soft elastic infrastructure (silty sand)

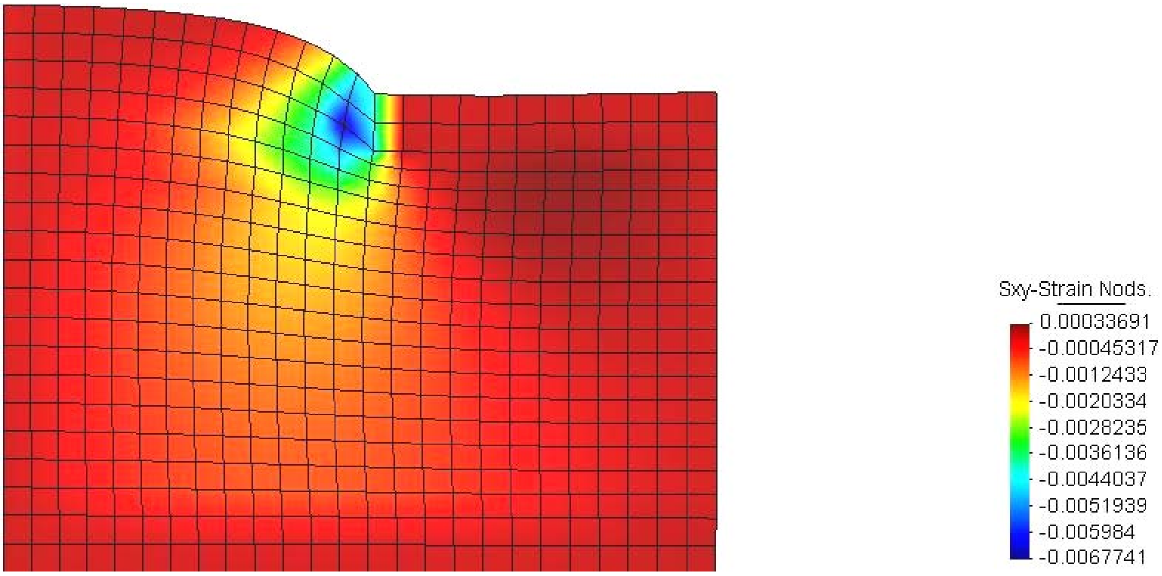
For a soft infrastructure, the displacements concern not only the ballast but the infrastructure too (figure 11) and the maximum value is 70% higher. Because of the soft infrastructure, the ballast displacement is more homogeneously distributed under the sleeper, and the sleeper itself has a lower deflection. Between the sleeper centre and the corner, the vertical displacement difference is only 50% the one on a stiff infrastructure.

Figure 11 Displacements, soft elastic [m]



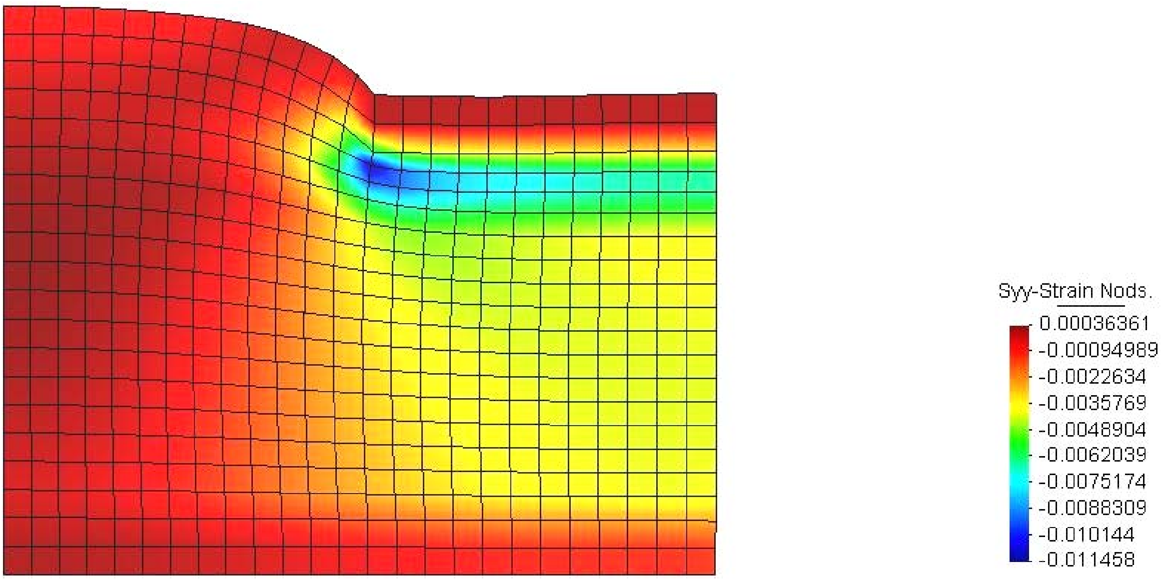
The shear strains (figure 12) are more concentrated but are 20% higher. This should be due to the fact that the Poisson coefficient is higher, so the volume of silty sand remains more constant than in gravel (figure 10).

Figure 12 Shear strains, soft elastic



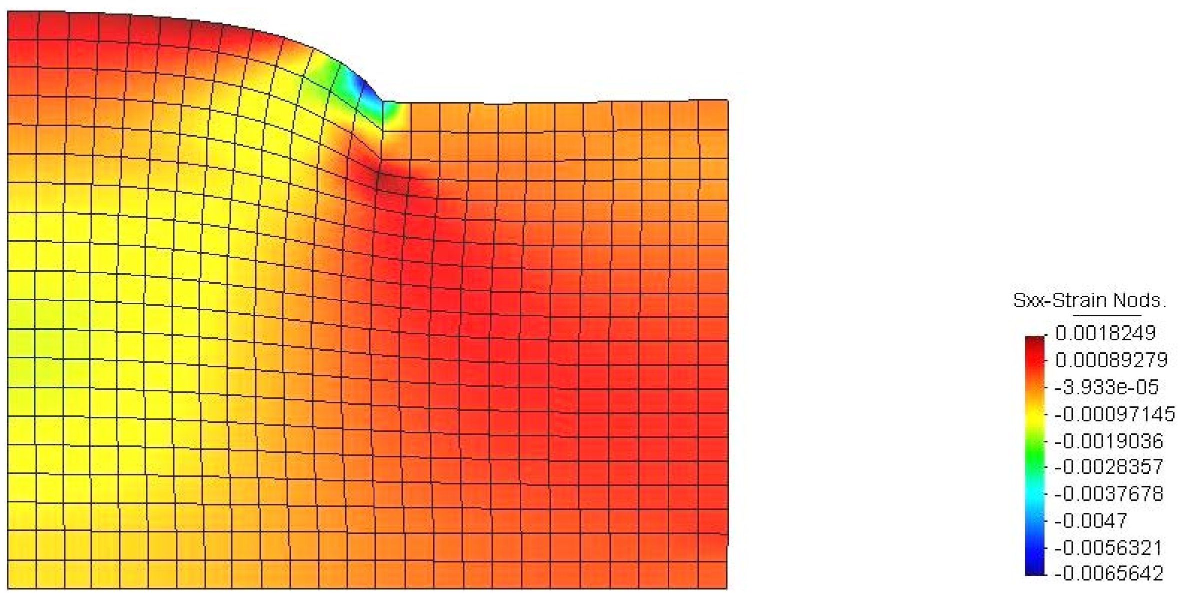
As the material is soft, vertical strains (figure 13) are high in the whole infrastructure: in the zone below the sleeper, it's twice higher, compared to the stiff material (figure 8). Nevertheless, the maximum in the ballast under the sleeper corner is the same.

Figure 13 Vertical strains, soft elastic



The horizontal strains show more variation between the zone underneath the sleeper and the one without sleeper. As we can see in the right side of figure 14, the strains in the ballast are lower and quite uniformly distributed, whereas with a stiff infrastructure (figure 9), strains in the ballast are much more inhomogeneous between the centre of the sleeper and its side.

Figure 14 Horizontal strains, soft elastic

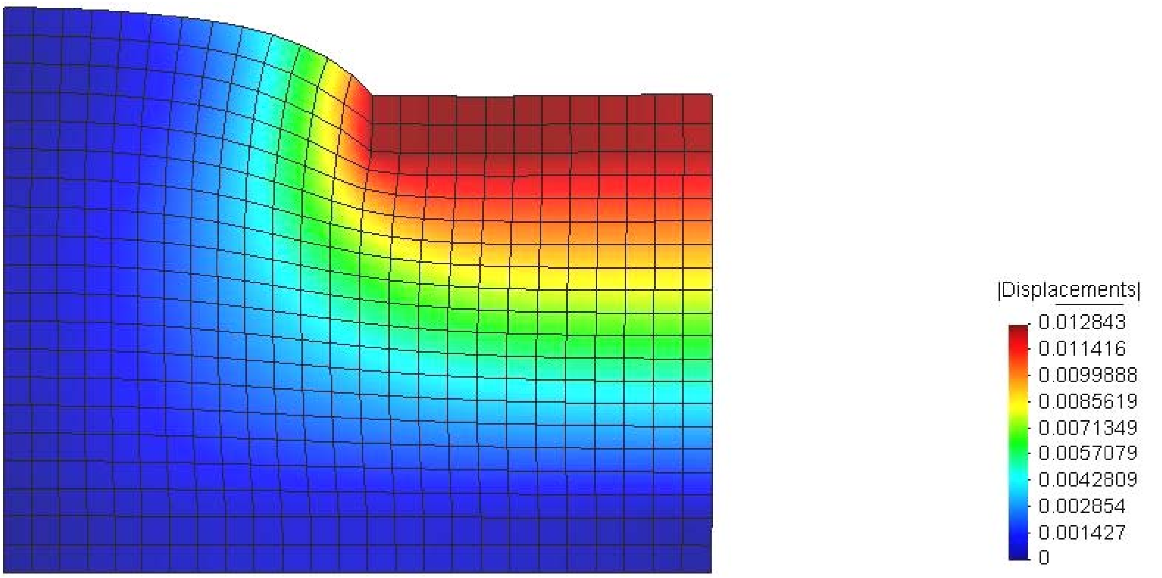


4.3 Soft elastoplastic Hujeux infrastructure (silty sand)

The response of a railway track structure to the traffic has been calculated again. This time the soft infrastructure is supposed to follow an elastoplastic Hujeux behaviour. The results are compared with the elastic infrastructure case.

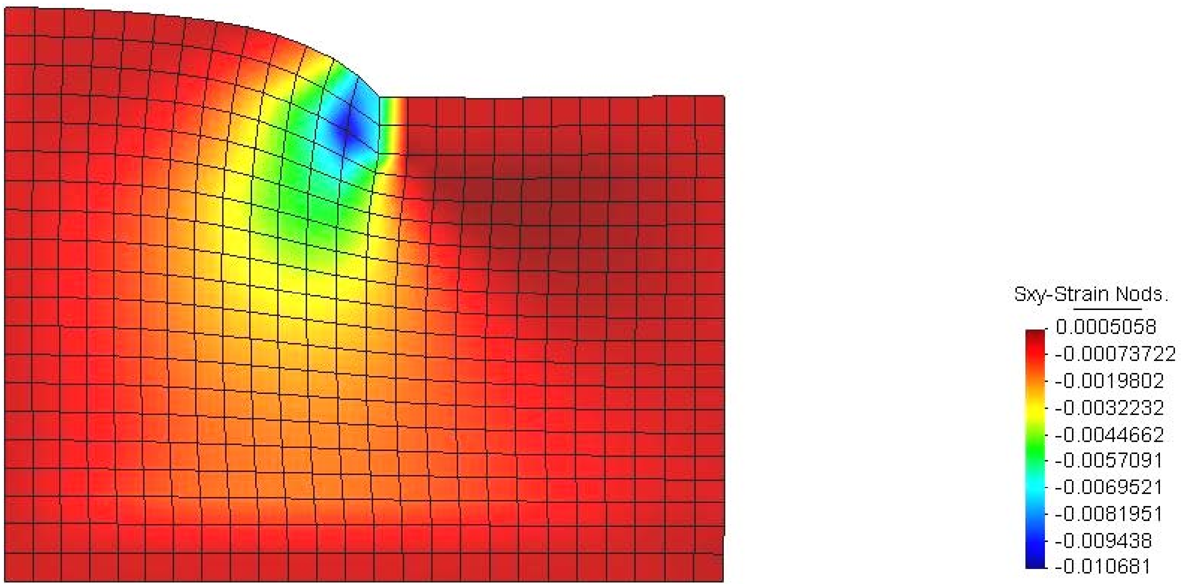
Concerning the displacements (figure 15), the results show that the infrastructure undergoes an important displacement: 10 mm against 5mm for the elastic model. Therefore, in this case, the soft layer is responsible of most of the complete structure deformation. The distribution of the displacements shows that the ballast and the infrastructure around the sleeper, at the external low corner, are more disturbed.

Figure 15 Displacements, soft elastoplastic Hujeux [m]



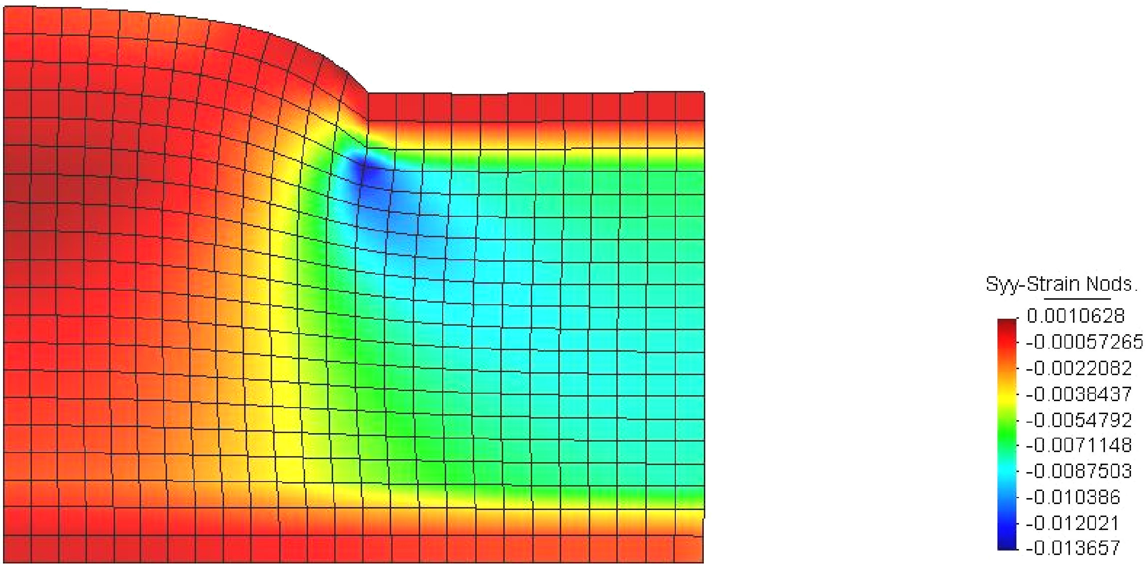
The shear strains (figure 16) are 60% higher in the whole infrastructure, compared to the elastic infrastructure case (figure 12). On the sleeper side, the most critical zone concerns not only the ballast, but also a significant part of the subgrade.

Figure 16 Shear strains, soft elastoplastic Hujeux



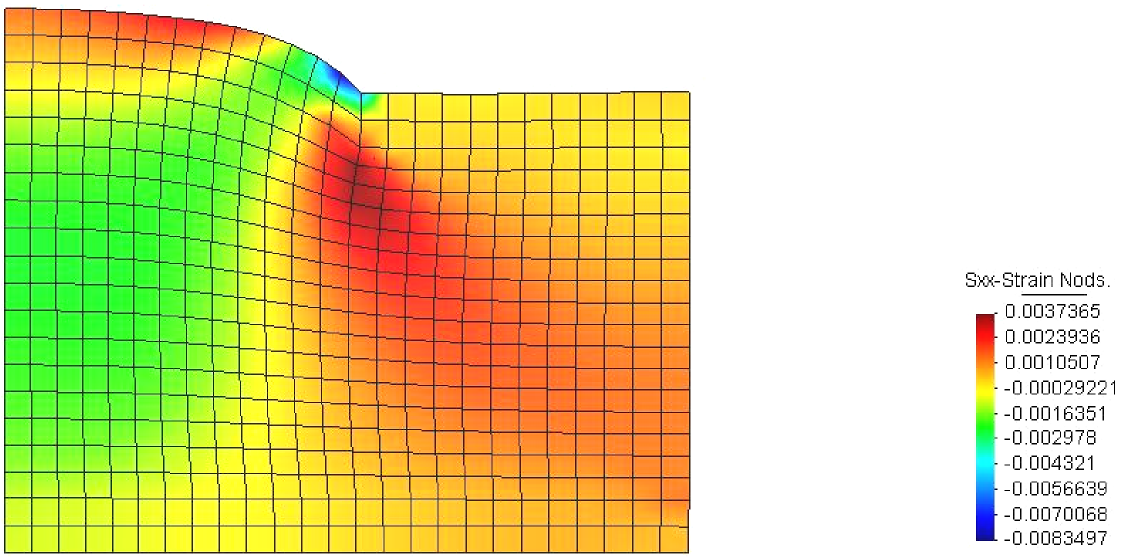
The vertical (figure 17) and the horizontal (figure 18) strains are also higher in the whole structure, compared to the previous case. The vertical strains are especially high in the subgrade layer zone under the sleeper are up to 100% bigger: this plasticization of the material explains also the severe displacements of the sleeper.

Figure 17 Vertical strains, soft elastoplastic Hujeux



The horizontal strains are also highly inhomogeneous: under the sleeper side, a large zone covering only the ballast but also the subgrade is very deformed.

Figure 18 Horizontal strains, soft elastoplastic Hujeux



5. Conclusions and perspectives

A two-dimensional finite element model has been developed to simulate the long-term behaviour of ballast under traffic loading and the settlements development. Ballast at different ages, and two types of infrastructure are simulated. Two behaviour laws are applied on the infrastructure: elastic and elastoplastic Hujeux with cyclical plasticity. Results are presented and compared.

The elastic stiff subgrade analysis shows that the ballast is the only responsible of the sleeper deflection, which is quite low. This is more important at the sleeper external side, where are also concentrated the highest horizontal and shear strains in the ballast. The stresses are very well dumped by the sleeper and the ballast.

In an elastic soft subgrade analysis, the infrastructure participates in the deformation, which is up to 70% higher. On the other side, the sleeper settles more homogeneously. The horizontal strains are more uniformly distributed.

The elastoplastic Hujeux model has been tested on the soft subgrade too. The results show important infrastructure displacements, and strains are up to 100% higher compared to the elastic model. The subgrade plasticization explains these important settlements.

This model is supported by laboratory tests on ballasts and infrastructures of different qualities. The evolution of the ballast behaviour is analysed with the measurement of the quasi-static module E, through plate bearing tests performed under sleepers, after traffic cycles and tamping operations. This measurement is very interesting, because it makes possible to follow the mechanical state of ballast in the zone of the track where it's the most loaded, during its lifetime.

The next step is a 3D analysis, covering 3 sleepers, because it can better represent the distribution of the traffic loads in the direction of the rails, under the sleepers and between them. The effect of close sleepers is important. This solution is supposed to show lower strains in the infrastructure.

In the laboratory hall, traffic simulation at real scale is performed. A hydraulic actuator loads the track continuously for 1 million cycles at a frequency of 4 Hz. Settlements, both in the ballast and in the infrastructure layers at different depths, are measured and integrated in the model. The settlement speed of different aged ballast is calculated and a phenomenological model is going to be developed.

This will make it possible to analyse separately the long-term effects of traffic loading and track tamping on ballast degradation and its consequent behaviour.

Knowing the ballast degradation permits to apply maintenance strategy in a less aggressive way in order to increase its lifetime and the durability of tamping operations. In this way maintenance costs for the railway companies can be decreased.

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