Prediction of permanent deformations of unbound pavement layers

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ABSTRACT: This paper presents a simplified method for modelling of permanent deformations of unbound granular pavement layers, using finite element calculations. This method is based on a model of prediction of permanent deformations of unbound granular materials, developped from repeated load triaxial testing [Gidel, 2001]. The permanent deformations in the pavement structure are calculated in two steps : The first step consists in modelling the resilient behaviour, using non linear elastic models, to determine the stress field in the pavement. The second step consists in using the stress paths obtained at different points in the pavement structure to calculate the permanent strains, using the permanent deformation model. The approach is used to predict the rutting of a low traffic pavement structure, with unbound granular base, tested on the LCPC accelerated testing facility.

KEY WORDS: Unbound granular materials, permanent deformations, pavement modeling, pavement performance.

1 INTRODUCTION

Low traffic pavements, with unbound granular bases, represent , in France, about 60 % of the road network. The main mechanism of deterioration of these flexible pavements is rutting of the unbound pavement layers and of the subgrade. In recent studies performed at LCPC, it has been observed that when the bearing capacity of the subgrade soil is sufficient, this rutting takes place mainly in the granular base and subbase layers.

Despite this fact, the rutting of unbound granular materials (UGMs) is still not well understood, and is seldom taken into account in pavement design methods. In the French pavement design method, based on linear elastic modeling of the pavement, the only rutting criterion concerns the subgrade, and consists in limiting the vertical elastic strain at its top.

In this paper, an attempt is made to develop a rational approach for predicting the rutting of unbound pavement layers, based on finite element calculations. This method is implemented in the finite element code CESAR –LCPC. It is based on the following principles :

1. The permanent deformation behaviour of unbound granular materials is described using an empirical permanent deformation model developed from repeated load triaxial testing. In the future, it is also planned to introduce in the program other models (elasto-plastic model for UGMs, model for rutting of bituminous materials).
2. The finite element method is used to calculate the permanent deformations in the pavement structure, in 3D. However, two methods are used to accelerate the calculations, and avoid calculating incrementally the response of the structure to large numbers of load

cycles. These methods are based on the fact that pavement loading conditions are characterized by large numbers of load cycles (10^5 to 10^6 for low traffic pavements), but with relatively low stress levels, leading to very small increments of permanent deformations per cycle. This makes it possible to calculate separately the resilient behaviour of the pavement and the permanent deformations, and also to calculate the permanent strain increment only at selected cycle numbers (assuming that it is constant in between).

3. the program allows to simulate complex loading histories of the pavement, including different types and positions of the loads, different loading speeds, different pavement temperatures and different values of the material parameters (to take into account seasonal variations of the water content in the unbound layers for example).

2 GENERAL PRINCIPLES OF THE METHOD OF PREDICTION OF PERMANENT DEFORMATIONS

2.1 General assumptions

The proposed calculation method is developed for flexible pavements, including a bituminous wearing course, bituminous or unbound granular base and subbase layers, and a subgrade. At this stage, only the permanent deformations of the unbound granular layers are taken into account, and the behaviour of the other materials is supposed purely resilient (linear elastic or visco-elastic for the bituminous materials, linear or non-linear elastic for the subgrade).

The approach for the calculation of the permanent deformations is based on 4 main hypotheses :

H1: the behaviour of UGMs is assumed elasto-plastic. The strains in these materials can be decomposed into an elastic strain component $\underline{\underline{\varepsilon}}^e$ and a plastic strain component $\underline{\underline{\varepsilon}}^p$:

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^e + \underline{\underline{\varepsilon}}^p \tag{1}$$

H2 : During one load cycle, the increment of plastic strain $\delta\underline{\underline{\varepsilon}}^p$ is assumed to be very small (negligible) in comparaison with the elastic strain :

$$\text{For one load cycle : } \delta\underline{\underline{\varepsilon}}^p << \underline{\underline{\varepsilon}}^e \tag{2}$$

H3 : It is assumed that the residual stresses $\underline{\underline{\sigma}}^{residual}$ generated by the accumulation of permanent strains are small in comparison with the stresses due to the traffic loads $\underline{\underline{\sigma}}^{load}$, and that they can be neglected :

$$\underline{\underline{\sigma}}^{residual} << \underline{\underline{\sigma}}^{load} \tag{3}$$

H4 : The elastic part of the behaviour is assumed to be invariable (it is assumed that it is not affected by the number of load cycles, nor by the level of plastic strains).

These hypotheses, and in particular H2 and H4 are well verified in repeated load triaxial tests on UGMs, with cyclic stress levels corresponding to real traffic loads as illustrated in figures 1 to 3. Figure 1 represents the response of the material in terms of axial stress – axial strain cycles. The response is characterized by a non linear stress-strain behaviour, and the accumulation of permanent strains. Figure 2 represents, for the same test; the variation of the amplitude of the cyclic elastic axial strain (or resilient strain) with the number of load cycles. Except during the first cycles, where it decreases, the elastic strain amplitude remains constant throughout the test. Figure 3 represents, again for the same test, the variation of the permanent axial strain increment per load cycle $\delta\varepsilon_1^p/\delta N$. This permanent strain increment decreases continuously, and rapidly becomes negligible in comparison with the elastic strain .

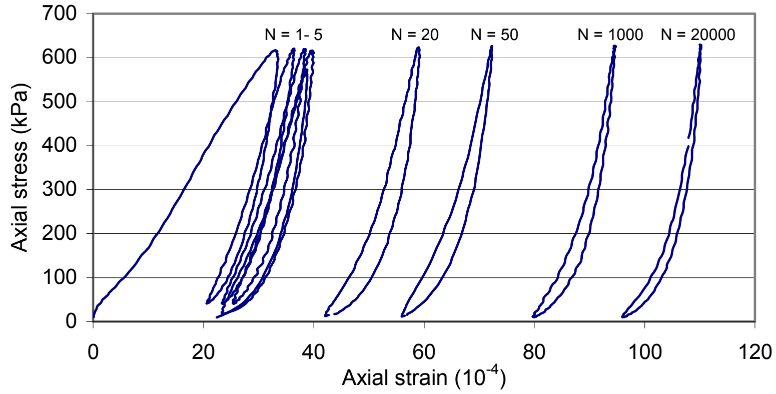


Figure 1 : axial stress – axial strain cycles obtained in a cyclic triaxial test on a UGM

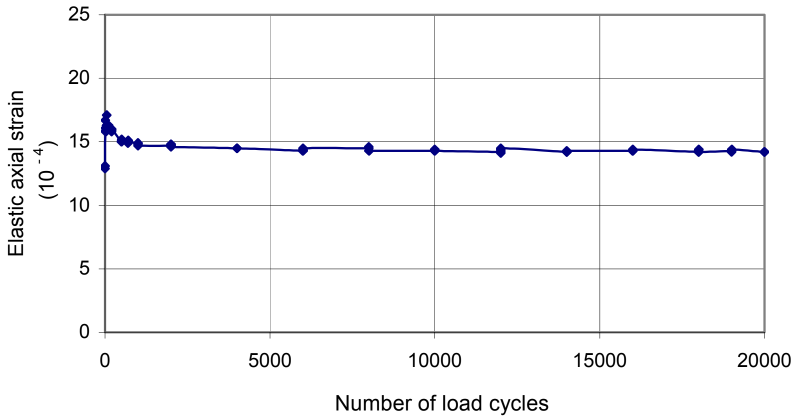


Figure 2 : variation of the cyclic elastic axial strain with the number of load cycles.

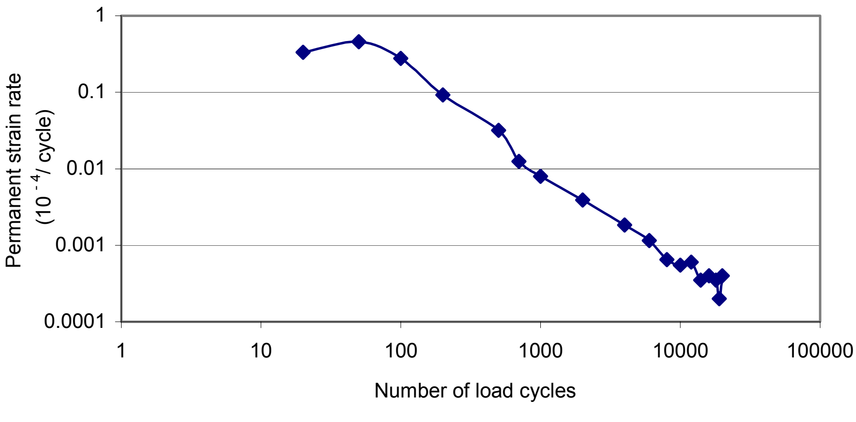


Figure 3 : evolution of the permanent axial strain increment per load cycle.

The previous hypotheses allow to simplify the calculation of the permanent deformations in the granular layers. In a first step, the plastic strains can be neglected, and the stress field in the pavement can be calculated using the elastic behaviour only. The plastic strains can then be calculated separately, in a second step, using the previously determined stress field.

2.2 Permanent deformation calculation procedure

The procedure for the calculation of the permanent deformations, is based on this decoupling of the calculation of the elastic response and of the plastic strains. It can be divided in 3 steps:

1. The first step consists in calculating the resilient response of the pavement, for the different loading conditions considered (different types of loads, different temperature, etc..).
2. Then the elastic stress fields are used to calculate the plastic strains produced by the successive application of the different loads. The permanent strains are calculated locally, at different points in the pavement structure, in 2D (in the plane (0,y,z) perpendicular to the direction of displacement of the load).
3. Finally, calculation of the permanent displacements in the pavement structure. The plastic strains being determined locally, at different points, they do not derive from a displacement field. It is thus necessary to determine the total strains, satisfying the cinematic compatibility condition, and the corresponding displacements

3 MODELS FOR THE CYCLIC BEHAVIOUR OF UNBOUND GRANULAR MATERIALS

The method of calculation requires to model both the resilient behaviour and the permanent deformation behaviour of unbound granular materials. This is done using models developed at LCPC, from repeated load triaxial tests.

3.1 Non linear elastic model

The model used to describe the resilient behaviour of unbound granular materials is a non linear elastic model proposed by Boyce [1980] and modified by Hornych et al. [1998] to introduce anisotropy of the materials. This leads to the following stress-strain relationships :

$$\varepsilon_v{}^* = \frac{1}{K_a}\frac{p^{*n}}{p_a{}^{n-1}}\left[1+\frac{(n-1)K_a}{6G_a}\left(\frac{q^*}{p^*}\right)^2\right] \quad \text{and} \quad \varepsilon_q{}^* = \frac{1}{3G_a}\frac{p^{*n}}{p_a{}^{n-1}}\frac{q^*}{p^*} \qquad (4,5)$$

with : $p^* = (\gamma\sigma_1 + 2\sigma_3)/3$ and $q^* = \gamma\sigma_1 - \sigma_3$ (6,7)

$$\varepsilon_v{}^* = \varepsilon_1/\gamma + 2\varepsilon_3 \quad \text{and} \quad \varepsilon_q{}^* = \frac{2}{3}(\varepsilon_1/\gamma - \varepsilon_3) \qquad (8,9)$$

K_a, G_a, n, and γ parameters of the model.

An example of adjustment of the anisotropic Boyce model on results of a cyclic triaxial test is shown on figure 4.

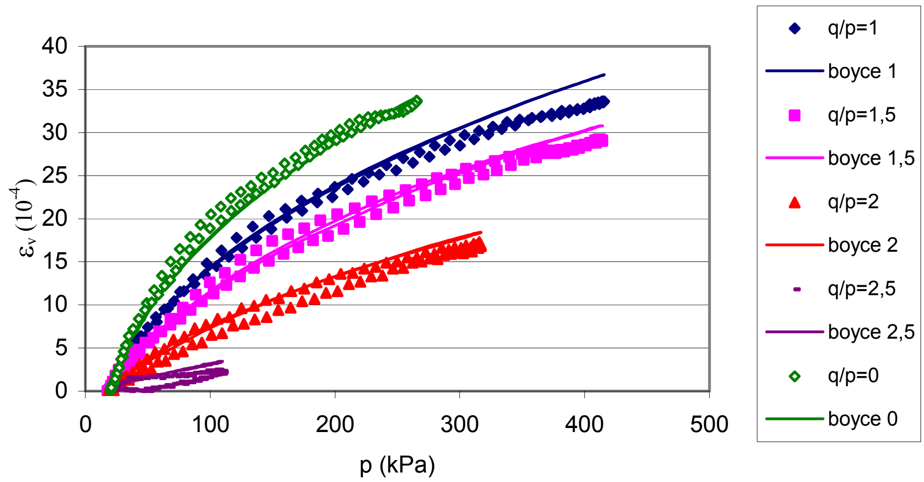


Figure 4 : example of adjustment of the anisotropic Boyce model.

This figure compares experimental and predicted resilient volumetric strains (strains during unloading) obtained for different stress paths q/p. The experimental resilient behaviour of the granular material is clearly non linear and depends both on the mean stress p and on the stress ratio q/p. This behaviour is well described by the model

3.2 Permanent deformation model

The permanent deformation model is an empirical model developed by Gidel et al. [2001]. This model describes the variation of permanent axial strains ε_1^p as a function of the number of cycles N and of the maximum cyclic stresses p_{max} and q_{max}. Its expression is :

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}})} \qquad (10)$$

with : $L_{max} = \sqrt{p_{max}{}^2 + q_{max}{}^2}$, $p_a = 100$ kPa, N_0 reference number of cycles, $\varepsilon_1{}^p{}_0$, B, n, m, s parameters of the model.

This empirical model has been implemented in the program first because of its simplicity; one of its drawbacks is that it describes only the variation of the permanent axial strains. Work is also under way to implement in the programme a more accurate, incremental, elasto-plastic model, also used at LCPC for unbound granular materials, the model of Chazallon [2000].

An example of prediction of results of a permanent deformation test with the model of Gidel is shown on figure 5. The test includes 4 sequences of loading of 50000 cycles each, with the same stress ratio q/p = 2, and with increasing stress amplitudes.

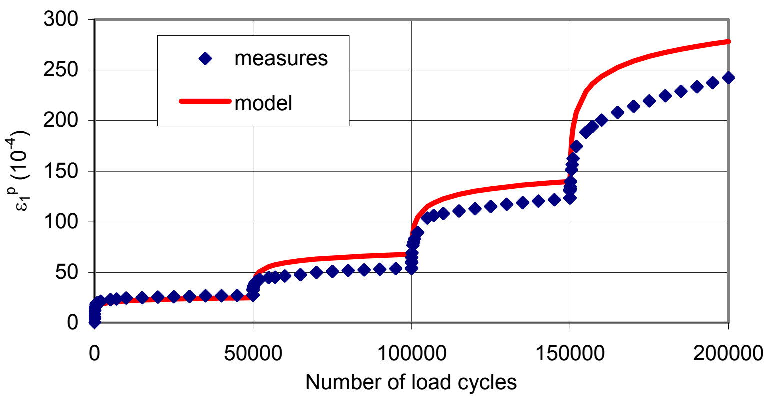


Figure 5 : example of prediction of a permanent deformation test with the model of Gidel.

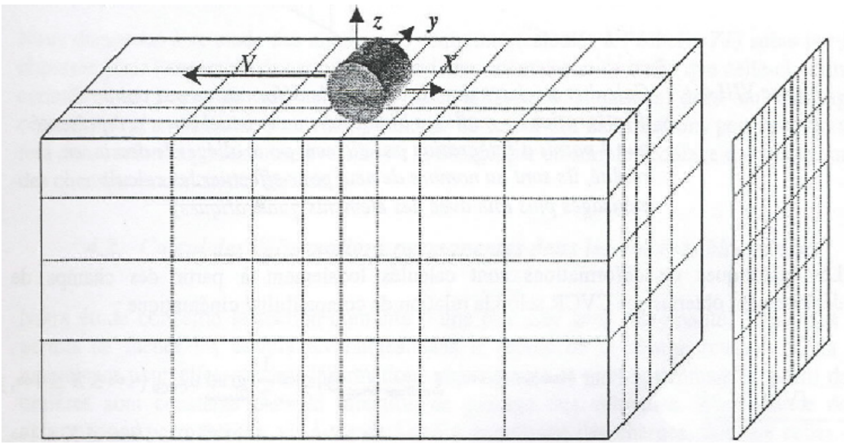
4 FINITE LEMENT CALCULATION OF THE PERMANENT DEFORMATIONS - THE PROGRAMME ORNI

The method of prediction of permanent deformations is implemented in the module ORNI of the finite element code CESAR-LCPC. The development of this module was started by Heck [2001], and it has been adapted by the authors to the prediction of permanent deformations of unbound granular layers.

4.1 Calculation of the resilient stress fields

The first phase consists in calculating the resilient stress fields corresponding to the different loading conditions of the pavement, which may include different sets of material parameters, different temperatures, different types of vehicles and different vehicle speeds and positions. These stress fields are calculated in 3D, using the module CVCR of CESAR-LCPC, which models the resilient behaviour of pavements under moving wheel loads [Heck and al., 1998]. This module includes several different constitutive models for pavement materials : linear elasticity, the Huet-Sayegh visco-elastic model for bituminous materials [Huet, 1963], and two non linear elastic models for granular materials : the modified Boyce model (§ 3.1) and the K-theta model [Hicks and Monismith, 1971].

The stress values calculated with CVCR, in 3D, must then be transferred to the module ORNI, which calculates the rut depth in 2D, in the plane Oyz perpendicular to the road axis (Ox). In general, the two finite element meshes do not coincide : in CVCR, a relatively coarse mesh is generally used, to save calculation time and in ORNI, a larger number of elements is required in the lateral direction (Oy), to increase accuracy, as shown in figure 6.



CVCR Mesh ORNI Mesh

Figure 6 : view of the finite element meshes used in the calculation method (the number of elements is reduced, for better comprehension)

To transfer the data from the CVCR mesh to ORNI, the following procedure is used : the nodal displacements calculated with CVCR, are used to calculate the associated strains at the Gauss points of the ORNI mesh (using the element shape functions); then the corresponding stresses are calculated by inversion of the non linear elastic constitutive law.

4.2 Calculation of the permanent strains

4.2.1 Description of the loading history of the pavement

To calculate the permanent strains, different time scales are considered in ORNI :

- The life of the pavement is divided in seasons; in each season the traffic and the material parameters can be different (to describe, for example, variations of water content in the unbound layers).
- During each season, the material parameters are constant. The season is divided in a number n_d of days. Each day is assumed to have the same daily temperature variations, and the same traffic.
- The day is divided in n_p periods, with a constant temperature in each period.

- To each period is associated a given traffic, defined by a statistical distribution of the loads (types of vehicles, vehicle speeds, vehicle lateral positions).

4.2.2 Calculation of the permanent strains for one period

For each period, to accelerate the calculations, it is assumed that the increments of permanent strains per load cycle are sufficiently small so that the order in which the different loads are applied has no influence. In this way, it is possible to calculate a mean increment of permanent strain, corresponding to a certain statistical distribution of the loads (load types, load positions, loading speeds), defined by :

- The number of different load types and the probability of occurrence of each load type $p_{load}(i)$.
- The number of different loading speeds and the probability of occurrence of each speed $p_{speed}(j)$.
- The number of different lateral positions of the loads, and the probability of occurrence of each position $p_{pos}(k)$.

Each of these 3 parameters is assumed independent of the others. The probability of occurrence of a given, combined, load situation (type of load, speed, position) can thus be calculated by :

$$p(i,j,k) = p_{load}(i)\times p_{speed}(j)\times p_{pos}(k) \tag{11}$$

And the mean increment of permanent strain for that period can be calculated by :

$$\delta\underline{\underline{\varepsilon}}^{p}_{mean}(N) = \sum_{i,j,k} p(i,j,k)\cdot \delta\underline{\underline{\varepsilon}}^{p}_{i,j,k}(N) \tag{12}$$

In this expression, $\delta\underline{\underline{\varepsilon}}^{p}_{i,j,k}(N)$ is the increment of permanent strain corresponding to one given combined load situation, calculated at cycle N, representing the first cycle of the period. (Note that each combined load situation corresponds to one stress field calculation with CVCR). Each value of $\delta\underline{\underline{\varepsilon}}^{p}_{i,j,k}(N)$ is calculated in the directions of the principal stresses, using the model of Gidel, (expressed as a product of a function of the number of cycles f(N) and a function of the maximum cyclic stresses $g(p_{max}, q_{max})$) in two steps :

- First, an equivalent number of load cycles N_{eq} corresponding to the actual cumulated permanent strain $\underline{\underline{\varepsilon}}^{p}$ is determined :

$$N_{eq} = f^{-1}\left[\frac{\underline{\underline{\varepsilon}}^{p}}{g(p_{max}, q_{max})}\right] \tag{13}$$

- Then, $\delta\underline{\underline{\varepsilon}}^{p}_{i,j,k}(N)$ is obtained by :

$$\delta\underline{\underline{\varepsilon}}^{p}_{i,j,k}(N) = \left[f(N_{eq}+2) - f(N_{eq}+1)\right]\cdot g(p_{max}, q_{max}) \tag{14}$$

Finally, the permanent strain increase for the period (comprising ΔN_i cycles) can be calculated by:

$$\Delta\underline{\underline{\varepsilon}}^{p} = \Delta N_i \times \delta\underline{\underline{\varepsilon}}^{p}_{mean} \tag{15}$$

assuming that the mean increment $\delta\underline{\underline{\varepsilon}}^{p}_{mean}$ remains constant during the period.

4.3 Calculation of the displacements (rut depths)

The calculation of the total displacements can be performed at any number of load cycles N defined by the user (this calculation is optional). To calculate these displacements, the equilibrium of the pavement in the absence of any traffic load is considered. In this condition, a small residual stress field $\underline{\underline{\sigma}}^r$ associated to the non-compatible plastic strains $\underline{\underline{\varepsilon}}^p$ subsists in the structure. The hypothesis made here is that these residual stresses will progressively dissipate, thus generating further strains. The additional strains, and thus the total strains $\underline{\underline{\varepsilon}}^{rut}$, can be obtained by assuming a linear elastic relationship between the residual stresses and the additional strains :

$$\underline{\underline{\sigma}}^r = \underline{\underline{\underline{\underline{E}}}}_0 : (\underline{\underline{\varepsilon}}^{rut} - \underline{\underline{\varepsilon}}^p) \tag{16}$$

Thus, the total strains $\underline{\underline{\varepsilon}}^{rut}$, and the associated total displacements can be determined by solving this linear elastic problem.

5 PREDICTION OF THE RUTTING OF AN EXPERIMENTAL PAVEMENT

This part presents a simplified application of the method to the calculation of the rut depth in a low traffic pavement structure, which has been tested on the LCPC accelerated pavement testing facility (summer 2003). It is assumed that the loads applied on the pavement are all identical (same value of the load, same position). This pavement structure consists of :

- An 8 cm thick bituminous wearing course;
- A 50 cm thick granular base and subbase (crushed gneiss);
- A clayey sand subgrade (thickness 2.20 metres), resting on a rigid concrete slab.

The characteristics of the bituminous concrete and the subgrade soil, supposed linear elastic, have been estimated by fitting of in situ deflexion measurements. Simulations with the software ALIZE (elastic calculations) led to the following structures :

- Structure 1 :Bituminous concrete : E = 2000 MPa, $\nu = 0.25$; Soil : E = 100 MPa, $\nu = 0.35$;
- Structure 2 :Bituminous concrete : E = 2200 MPa, $\nu = 0.25$; Soil : E = 100 MPa, $\nu = 0.35$.

During the experiment, the large part of the traffic (60 %) was applied at temperaures varying from 18 to 28°C; which explains the bituminous concrete modulus value corresponding to a mean temperature of 25°C.

The behaviour of the unbound granular material was simulated using the non-linear elastic model and the permanent deformation model described in §3. The values of the model parameters are given in table 1.

Table 1 : values of model parameters used for the modelling of the unbound granular material

Non linear elastic model parameters				Permanent deformation model parameters				
K_a MPa	G_a MPa	n	γ	$\varepsilon_1{}^p{}_0$ (10^{-4})	B	n	m	s kPa
19.5	23.0	0.320	0.285	88.3	0.038	0.76	2.25	35.5

5.1 Determination of the stress paths in the granular layer

The first step consists in determining the stress paths in the granular layer from the CVCR results. These stress paths (and the permanent strains) are calculated in the plane (0,y,z) perpendicular to the direction of movement of the load. In our case, the load consists of 2 twinned wheels, with a total load of 65 kN.

Figure 7 shows examples of stress paths obtained with this approach, at different depths z, under the centre of one wheel (position y = 0.185 m). In the (p,q) stress space, these stress paths are practically linear, with values of slopes q/p between approximately 2 and 2.5. This is also true at other points in the granular layer and confirms that the stress paths in the pavement are very close to those applied in the permanent deformation triaxial tests (linear stress paths, with slopes q/p = 1, 2 and 2.5).

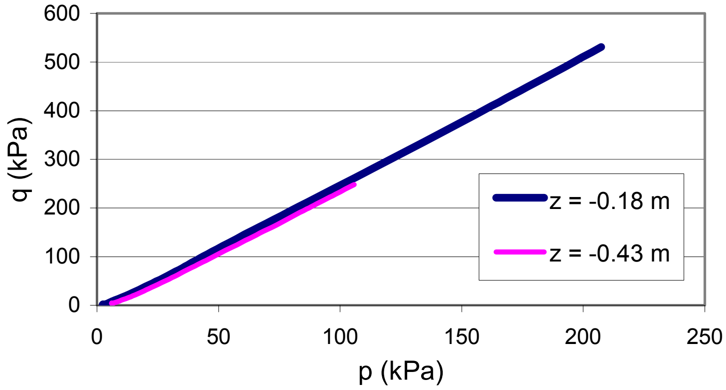


Figure 7 : stress paths in the granular layer, under the centre of one wheel, at different depths.

5.2 Ruth depth calculation

In our example, the maximum ruts depth after one million load cycles, are calculated under the centre of one wheel, where the stresses in the granular layer are maximum. Figure 8 shows the comparison between the measurements observed on the flexible pavement and the predictions performed with the rut depth calculation method on the two structures.

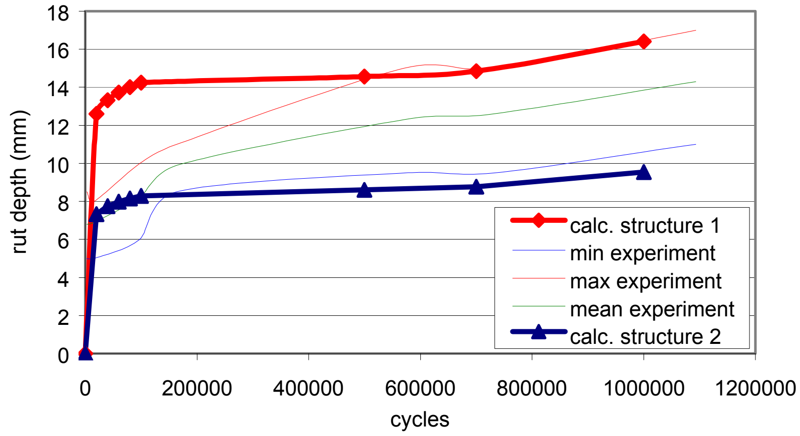


Figure 8 : comparison between rut depth measured on the flexible pavement and the modelling

After one million load cycles, the two calculations lead to values of rut depth close to the minimum and maximum of the experimental values (respectively 11 and 17 mm). However, the evolution of rutting during the 100 000 first load cycles is not well described by the model. This could be due to the difference between the initial state of the material in the field and in the laboratory tests, and to the difference in loading conditions.

These first simulations give encouraging results, but a more detailed study is planned to test the influence of the various modeling hypotheses on the rut depth predictions; the effects of the variations of the pavement temperature, and the influence of moisture content variations in the unbound layers will also have to be studied.

6 CONCLUSION

A simplified method for modelling of permanent deformations of unbound granular pavement layers, using finite element calculations, is described. This method is based on a simple permanent deformations model, developped recently from repeated load triaxial testing. An application of the method to the prediction of rutting of a real flexible pavement, considering only one type of load, and constant pavement material parameters is presented. The permanent deformations obtained after 1 million load cycles are close to those measured in situ, but the initial evolution of the rut depth (up to 100 000 cycles) is not well described. Further work is planned to evaluate and validate the rut depth calculation method, and extend it to take into account the contribution of the other pavement layers to rutting.

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