Advanced Numerical Study of the Effects of Road Foundations on Pavement Performance

X. Liu
Section of Structural Mechanics, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

A. Scarpas
Section of Structural Mechanics, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

ABSTRACT: In the current pavement design method, the pavement structure is treated normally as multi-elastic and fully bonded layer system. The influence of the nonlinear characteristics and the interaction of the individual layers on the pavement response are not considered. This is not much of a problem for a traditional construction, but ever more new constructions are requiring such an integral approach. The reason for this lies in their increased scale and complexity, and the application of new techniques and materials/material combinations. In this paper, the mechanical response of an asphalt concrete pavement, typical of Dutch conditions, has been studied on the basis of wheel tracking simulations. The finite element system CAPA-3D developed at the Section of Structural Mechanics of TU Delft has been utilized as the numerical platform for this study. In order to characterize the significance of the influence of the road foundation on the pavement performance, the effects of water content of the granular road base layer on the mechanical response of the pavement have been studied. The finite element simulation shows the development of strains and stresses inside the body of the pavement. Evaluation of the development of strain and stresses inside the body of the pavement indicate the reasons for the observed differences in permanent surface deformation from case to case. The results of the analyses indicate that the characteristics of road foundation can influence significantly the pavement response.

KEY WORDS: Finite element simulation, pavement, foundation, damage, water content.

1 INTRODUCTION

In a country like the Netherlands, construction of pavement in/on/with weak/wet subsoils is inevitable. Roads constructed on weak/wet subsoils often become uneven because of non-even settlements of the pavement surface. As soon as differences in the settlement start compromising comfort and safety of the traffic, road authorities have to apply maintenance measures. The need of regular maintenance of roads does not only add significantly to the cost of infrastructure, but is also a nuisance to road users. Thus the challenge for road authorities, designers and contractors is clear: the rapid construction of affordable road infrastructure with minimized maintenance requirements.

In general, the Dutch road network can be considered to be good and robust, especially when compared to the condition of the road system in many other countries. Nevertheless, yearly road inspections reveal that many roads still have much shorter life than expected. The reasons for this are many. In areas where clay or peat forms the wet subgrade of the pavement, most of the premature damage may be attributed to underestimating the influence of poor foundations on the life of the pavement structure.

Within the framework of the Delft Cluster program and under the auspices of CUR Bouw & Infra and CROW, the new workgroup 'Integraal wegontwerp' (Integral Road Design) has been established. Starting from the knowledge and innovations developed by Delft Cluster, the workgroup shall formulate guidelines and recommendations for the design and construction of better roads. There is yet no approach where strength and deformation of the foundation and the pavement superstructure are treated and included in the analysis in an integral manner. The goal of this study is the development of numerical techniques which enable the integration between pavements and underground infrastructures and break the traditional distinction between 'pavement' and 'foundation'.

In the first part of this paper, the material constitutive models are presented and its use for describing the nonlinear behaviour of the asphalt concrete. This includes description of the flow surfaces and the general constitutive framework. The mechanical response of asphalt concrete pavements, typical of Dutch conditions, has been studied on the basis of wheel tracking simulations. In order to characterize the significance of the influence of water content of the granular road base layer on the mechanical response of the pavement, a numerical example has been studied.

The finite element system CAPA-3D (Scarpas and Liu, 2000) developed at the Section of Structural Mechanics of TU Delft has been utilized as the numerical platform for this study. The finite element simulation shows the development of strains and stresses inside the body of the pavement. The importance of the damage distribution in the mixes and the road foundation materials is demonstrated. Evaluation of the development of strain and stresses inside the body of the pavement indicates the reasons for the observed differences in permanent surface deformation from case to case. The results of the analyses indicate that the water content in the granular base can influence significantly the pavement response. In order to represent more the real pavement situation, the concept of integral pavement structure has to be taken into account for the pavement design.

2 MATERIAL CONSTITUTIVE MODELLING

2.1 Hardening and Softening Behaviour of Asphalt Concrete

In this study, the characteristics of the constitutive model that is used for simulation of the response of asphalt concrete mix are presented. Due to the differences in the response of asphalt concrete between compression and tension test, aspects of the simulation of the compressive response are discussed first and then aspects related to the tensile response. The compressive response model utilized in this study for modeling granular material can be founded in Liu et al. 2004.

2.1.1 Flow Surface Characteristics

The material constitutive model, which is used to describe the response of the asphalt mixtures is based on the flow surface proposed originally by Desai (1980) and further developed by Scarpas (1997), Erkens (2002), Liu (2003) and Medani (2006).

The chosen form of the surface is given by:

$$F = \frac{J_2}{p_a^2} - \left[-\alpha \cdot \left(\frac{I_1 + R}{p_a} \right)^n + \gamma \cdot \left(\frac{I_1 + R}{p_a} \right)^2 \right] = 0 \tag{1}$$

where I1 is the first and J2 is the second stress invariants respectively, p_a is the atmospheric pressure with units of stress, R represents the triaxial strength in tension. In 3D space, Equation (1) represents a closed surface, as shown in Figure 1. The value of the yield function F determines the response of the material to a state of stress.

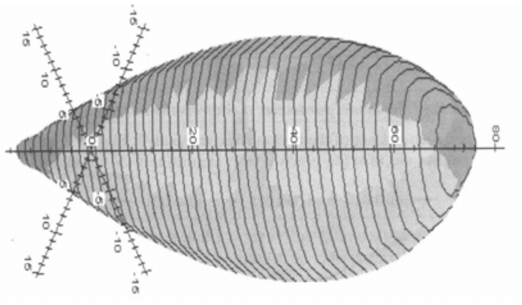


Figure 1: 3D representation of Desai response surface

The value of α controls the size of the flow surface. It is typically defined as a function of deformation history. As α decreases, the size of the flow surface increases so this parameter controls the hardening of the material. When $\alpha = 0$, the ultimate stress response surface of the material is attained.

Parameter γ is related to the ultimate strength of the material. It denotes the slope of the ultimate stress response surface. As γ increases, the slope of the ultimate response surface increases.

2.1.2 Asphalt Concrete Hardening

As discussed earlier, parameter α in the model controls the size of the flow surface. In the constitutive model it is postulated to be a function of the plastic deformation history. In the framework of this investigation, on the basis of laboratory tests for the mixture, the following relationship was found between α and the effective plastic strain ξ over the range of test data:

$$\alpha = \frac{\alpha_0}{\xi_{\lim}} \left(\xi_{\lim} - \xi \right) \exp\left(-\kappa_\alpha \xi \right) \tag{2}$$

where α_0 is the α value that corresponds to the initiation of plasticity, $\xi_{\lim}$ is the value of the effective inelastic strain at peak stress and κ_α is a material hardening parameter. Non-linear curve fitting over the available data sets results to the expression of κ_α for the mixture:

$$\kappa_\alpha = \kappa_{\alpha_1} \left[1 - \exp\left(-\left(\beta_T \cdot \dot{\varepsilon} \right)^{\kappa_{\alpha 2}} \right) \right] \tag{3}$$

where T and $\dot{\varepsilon}$ are the temperature and strain rate respectively.

2.1.3 Asphalt Concrete Softening

An isotropic measure of the degradation response can be introduced into the model to simulate the softening response. This can be done by means of specifying the variation of the model parameter γ, after the initiation of the degradation response, as a decaying function of a monotonically increasing physical quantity (e.g. equivalent post fracture strain ξ^{pf}), strain rate $\dot{\varepsilon}$ and temperature T. The expression of γ is given by:

$$\gamma = \gamma_{\min} + \left(\gamma_{\max} - \gamma_{\min}\right)\exp\left[-\eta_1 \left(\xi^{pf}\right)^{\eta_2}\right] \tag{4}$$

in which γ_{max} and γ_{min} are the value of γ at the point of peak stress and the point of complete annihilation of the material respectively. η_1 and η_2 are material constants. The material constant $\gamma_{\min}$ is given by:

$$\gamma_{\min} = \gamma_{\min 1} + \gamma_{\min 2}\left(\dot{\varepsilon} \cdot \beta_T\right)^{\gamma_{\min 3}} \tag{5}$$

in which $\gamma_{\min i}$ $(i = 1 - 3)$ are material constants.

The material constant η_1 is given by:

$$\eta_1 = \eta_{11}\left(\dot{\varepsilon} \cdot \beta_T\right)^{\eta_{12}} \tag{6}$$

where η_{11}, η_{12}, η_1 and η_2 are material constants.

2.2 Cracking

The tension softening model proposed by Scarpas and Blaauwendraad (1998) is used. This implies that for states of stress exceeding the magnitude of the fracture surface, a plane of cracking is introduced perpendicular to the principal tensile stress direction. On the crack plane a Hoffman response surface is specified to control the subsequent softening response. The following expression is proposed for the softening in tension:

$$\sigma_t = f_t \cdot e^{-k_t \xi^{pf}} \tag{7}$$

$$\kappa_t = \kappa_{t_1} \cdot \left(\beta_T \cdot \dot{\varepsilon}\right)^{\kappa_{t_2}} \tag{8}$$

in which σ_t is the tensile stress, $\kappa_{\alpha i}$ (i = 1 – 2) are material constants.

2.3 Parameter Determination and Model Verification

The parameters of the asphalt concrete constitutive model can be determined by using results of uni-axial monotonic compression and tension tests. The procedure of the parameter determination can be founded in Scarpas et al. (1997), Liu (2003) and Medani (2006). Both the capability of the model and the accuracy of the determination of the parameters can be examined by comparing the numerical predictions of the material response with the observed laboratory behaviour. The proposed constitutive model for asphalt concrete mix has been calibrated and verified with the test data. Figure 2 presents two comparisons of the numerical predictions with the results of monotonic compression tests. It is observed that the numerical predictions obtained from the constitutive model show good agreement with the experimental results. Figure 3 shows the numerical predictions for simulation of tensile response.

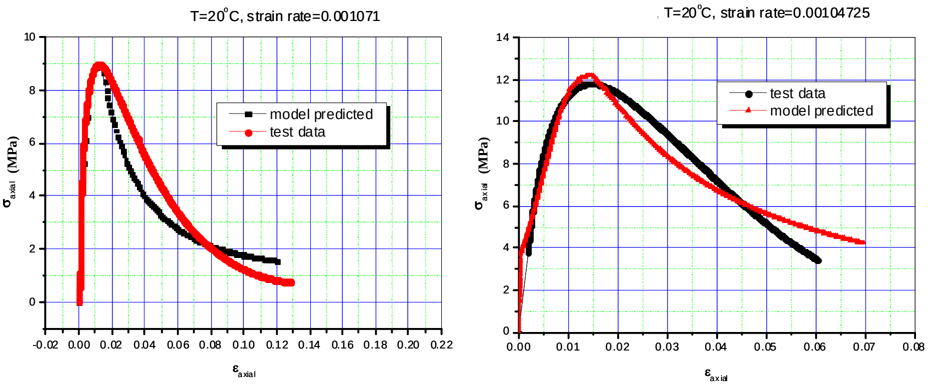


Figure 2: Numerical predictions and actual test data of compression test

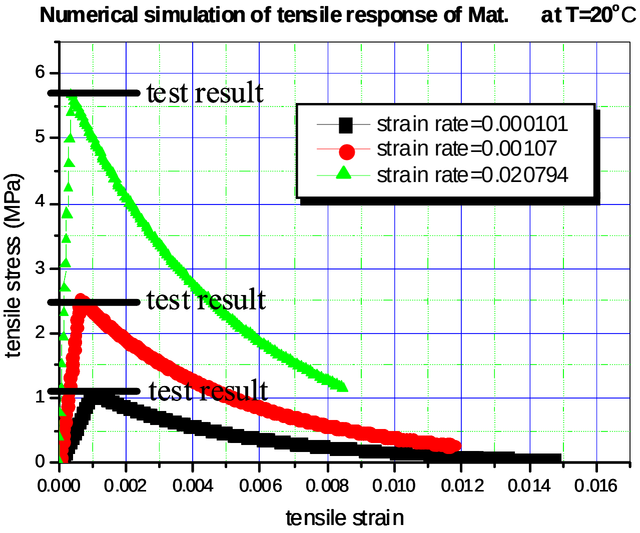


Figure 3: Numerical strength predictions and actual test data for tension tests

3 FINITE ELEMENT INVESTIGATIONS OF THE EFFECTS OF WATER CONTENT IN GRANULAR BASE ON PAVEMENT RESPONSE

3.1 Numerical Example

Water content of the granular base and subgrade is one of the most important environmental factors that influence pavement performance. The change in water content in the granular base and subgrade affects their stiffness and alters the stress state throughout the pavement but it may also cause increased strains in the AC layers by reducing the support available.

The objective of this study is to quantify the effects of water content of the granular base on the mechanical response of an asphaltic pavement by means of the finite element simulation. The pavement profile was assumed to consist of four material layers, Figure 4. The top layer represents a layer of asphalt concrete with a thickness of 0.15m. The granular base has thickness of 0.25 m. The sand base is assumed fully saturated with a thickness of 0.6m. The bottom layer represents a layer of clay subgrade with a thickness of 1.2m. Because of symmetry, only a half of the pavement width is modelled.

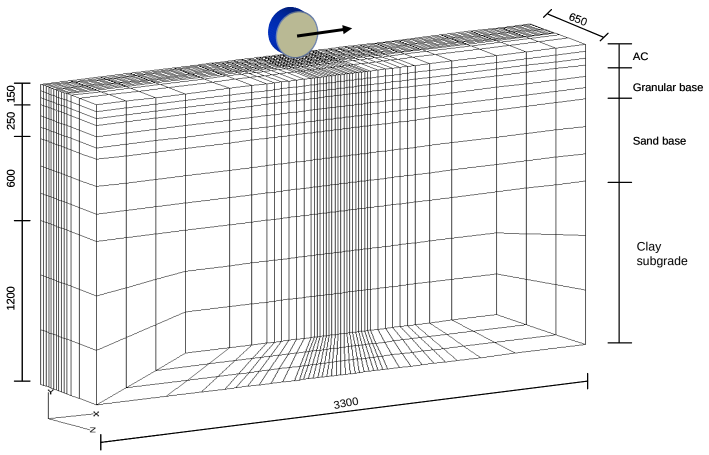


Figure 4: Finite element mesh for moving wheel-load analyses

The dynamic analysis option was utilized to subject the model to moving single wheel-loading. In order to reduce the dynamic wave reflection, layers of impendence element were introduced to the boundaries of the mesh. The single moving wheel load with speed 60 km/h was applied on the top of the pavement. An axial load of 100kN was considered. Uniform tire pressure (0.8 MPa) and corresponding contact shape of the imprints were utilized in the FE models.

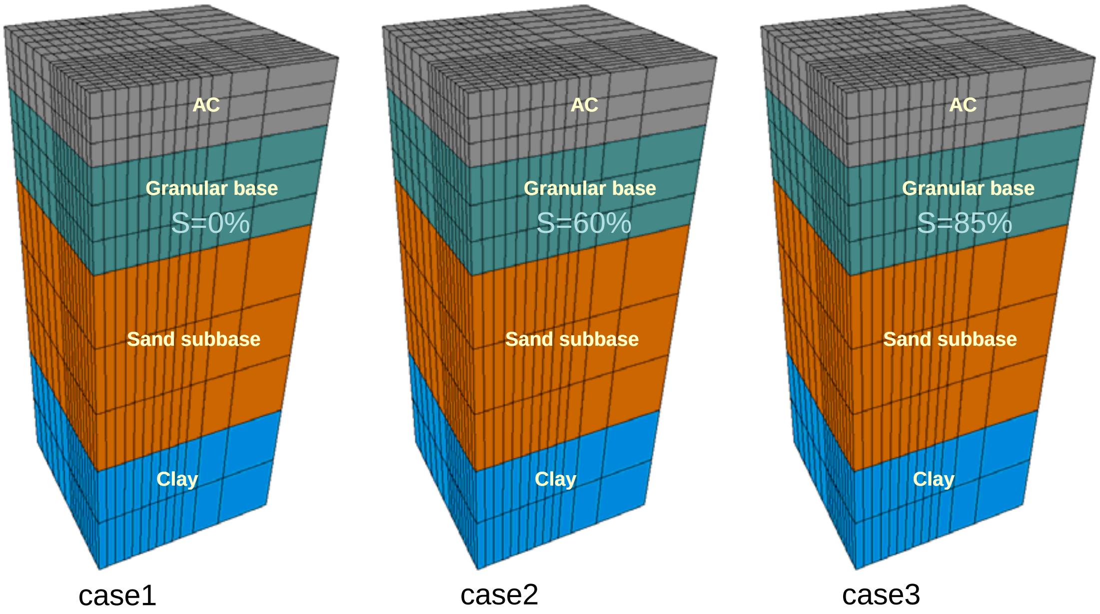


Figure 5: Scehematic FEM cases study

Table 1: List of material model parameters

Table 1	AC	Sand subbase	Clay
Young’s modulus (MPa)		80	25
Poisson’s ratio	0.35	0.31	0.31
Mass density (kg/m^3)	2350	1750	1700
φ (o)	--	35	25
c (kPa)	--	0.0	5.0

In the numerical simulations, all materials in the analyses were assumed with nonlinear material properties. The subgrade layers were assumed to be fully saturated with water. In order to investigate the influence of the change of water content in the granular base layer on pavement response, the following three cases have been investigated, Figure 5:

Case 1: The granular base was assumed in dry condition.
Case 2: The granular base was saturated with 60% water content.
Case 3: The granular base was saturated with 85% water content.

Table 1 shows the basic material parameters. The stiffness of the asphalt concrete is determined on the basis of the strain rate and temperature. The influence parameters of water content on resilient modulus of granular material were obtained from Rada and Witczak (1981). The resilient modulus tests were performed at two different degrees of saturation (60 and 85%) on crushed stone. The stress dependence of the resilient modulus of the granular base material was represented by $k-\theta$ model:

$$M_R = k_1\theta^{k_2} \tag{9}$$

where $\theta = \text{bulk stress}\ (\sigma_1 + \sigma_2 + \sigma_3)$ and k_1 and k_2 are moisture dependent model fitting parameters (Table 2). The influences of bulk stress on the resilient modulus of the granular base at two different saturation conditions are plotted in Figure 6. This model was utilized also by Zuo et al. (2007) to compute the effects of water content variation at the instrumented sites in Tennessee.

In the following, the response of each individual case is discussed first and some general conclusions are then drawn.

Table 2: List of moisture dependent model parameters

Table 2	S=60%	S=85%
k_1 (kPa)	498.2	49.6
k_2	0.5	0.7

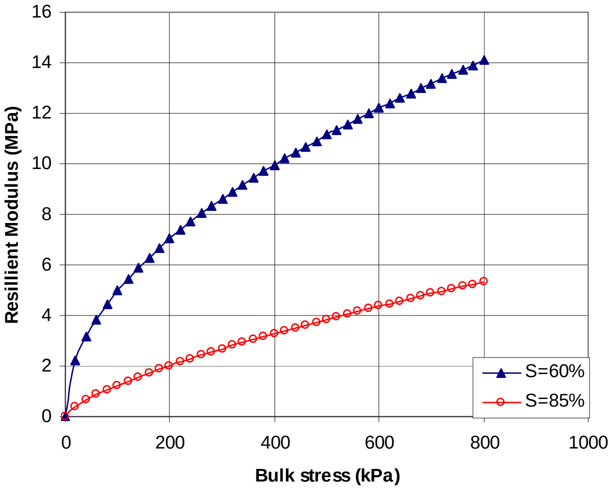


Figure 6: The influence of bulk stress on M_R

3.2 The Response of the Pavement under Granular Base Conditions

Figure 7 presents the comparisons of normal strain distribution through the whole layer of the pavement with case 1, 2 and 3 situations after 700 cycles. It can be observed that, for pavement with 85% water content in the granular base, the tensile strain along the transversal directions at the bottom of asphalt layer is 2 times higher than the pavement with 65% water content in the granular base and 4 times higher than the pavement with dry granular base condition. It can also be observed that almost 6 times higher vertical compression strain occurs on the top of the granular base layer with higher water content than case with dry granular base condition.

Also shown in Figure 8 is the comparison of the normal stress distributions along the depth of the pavement of case 1, 2 and 3. It can be observed that, due to the reduction in strength in granular base with increasing water content, both higher transversal and longitudinal tensile stresses are developed at the bottom of the asphaltic concrete layer in case 3 situation. The maximum tensile stress in case 3 along transversal direction at the bottom of the asphaltic concrete layer is 4 times higher than the one in case 1.

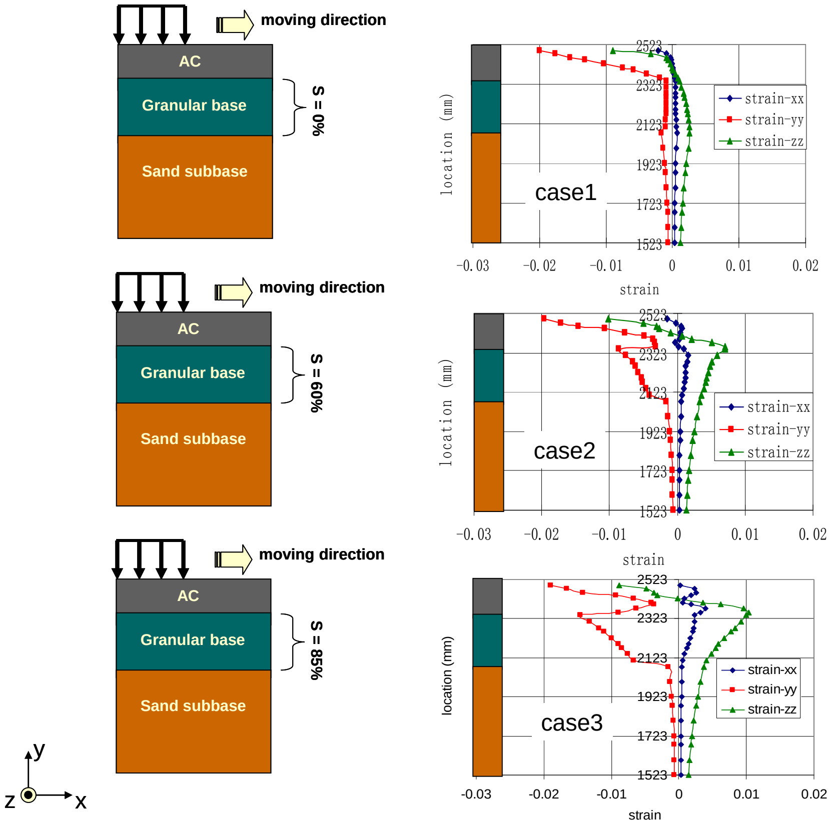


Figure 7: Normal strain distributions in pavement with different base conditions

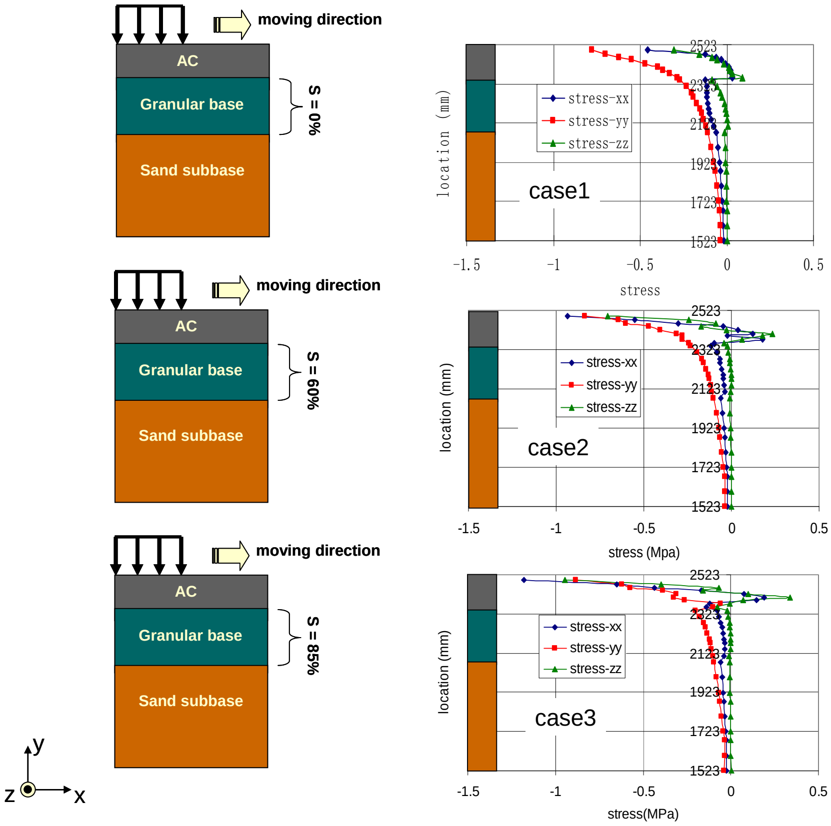


Figure 8: Normal stresses distributions in pavement with different base conditions

Figure 9 shows that the water content in granular base affects also the shear stress distribution throughout the pavement. For the three compared cases, higher shear stresses always occur in the middle of the asphaltic concrete layer. The highest shear stresses are developed in the case 3 and lowest ones are in the case 1.

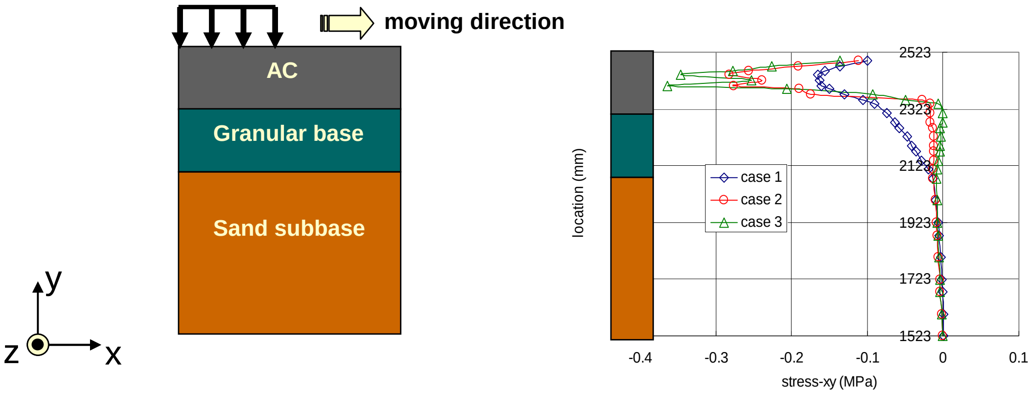
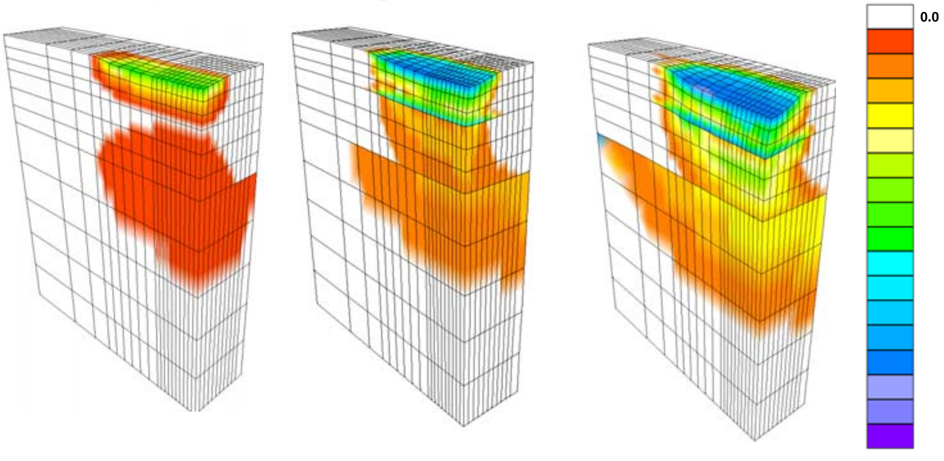


Figure 9: Shear stress-xy distributions in pavement with different base conditions



Case1 (S=0%) Case2 (S=60%) Case3 (S=85%)

Figure 10: Damage distribution inside the pavement with different conditions

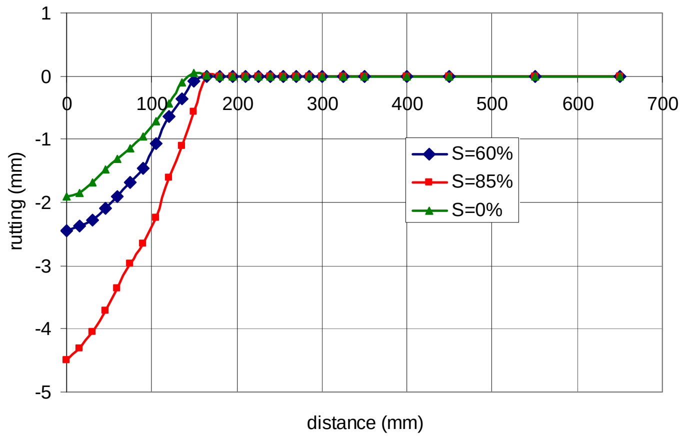


Figure 11: the rutting profile for the three type conditions after 700 cycles

After 700 of traffic load cycles, Figure 10 shows the development of the inelastic deformation in the pavement with different water content in road foundation. It can be observed that, at the top layer of the pavement in all cases, the region of intense concentration of the inelastic deformation in the vicinity of the wheel can be identified. With increasing number of load cycles the inelastic deformation spreads gradually towards the underlying layers of the asphalt pavement. It can be observed that in pavement of case 1, there are less inelastic deformations developed in the clay subgrade layer. However, for case 2 and 3, due to the influence of water content on the stiffness of granular material, the inelastic deformations are developed also into the clay subgrade layer. Figure 11 shows the comparison of the surface rut between the pavements of three cases after 700 traffic load cycles. It can be observed that the maximum rut depth occurring in the pavement of case 3 with higher water content in road base is almost 2.25 times higher than the pavement of case 1 with dry road base assumptions.

4 CONCLUSIONS

The effects of seasonal variation in water content in base layer have been studied using the finite element method. The environment data originated from Rada and Witzcak (1981).

Results of the analyses indicate that the change in water content in the base layer can influence the strain and stress distribution in pavement significantly.

Because of the influence of the water content on the stiffness of the base material, the estimated pavement life will be reduced. Furthermore, the effects of the material nonlinearity and water contents of base material cannot be considered separately and superimposed. It is important to consider the combined effect of material nonlinearity and water content in pavement design.

REFERENCES

Desai, C.S., 1980. *General Basis for Yield, Failure and Potential Functions in Plasticity*. International Journal of Numerical Analytical Methods in Geomechanics, 4, pp.377-387.

Erkens, S.M.J.G., 2002. *Asphalt Concrete Response (ACRe), Determination, Modelling and Prediction*. PhD. Thesis, Delft University of Technology, The Netherlands..

Liu, X., 2003. *Numerical Modelling of Porous Media Response Under Static and Dynamic Load Conditions*. PhD. Thesis, Delft University of Technology, The Netherlands.

Liu, X., Cheng, X.H., Scarpas, A. and Blaauwendraad, J., 2004. *Numerical modelling of nonlinear response of soil, Part 1: Constitutive model*. Int. J. Solids and Stru. 42(7), 1849-1881.

Medani, T.O., 2006. *Design Principles of Surfacings on Orthotropic Steel Bridge Decks*. PhD Thesis, Delft University of Technology, The Netherlands.

Rada, G. and Witzcak, M.W., 1981. *Comprehensive Evaluation of Laboratory resilient Moduli Results for Granular Material*. Transportation Research Record 810, Transportation research board, Washington D.C., pp.73-82

Scarpas, A, Gurp, C.A.P.M. van, Al-Khoury, R.I.N. and Erkens, S.M.J.G., 1997. *Finite Element Simulation of Damage Development in Asphalt Concrete Pavements*. 8th International Conference on Asphalt Concrete Pavements, Seattle, Washington, U.S.A.

Scarpas, A., and Blaauwendraad, J., 1998. *Experimental Calibration of a Constitutive Model for Asphaltic Concrete*. In: proceeding of Euro-C Conference on the Computational Modelling of Concrete Structures, Badgastein, Austria.

Scarpas, A. and Liu, X., 2000. *CAPA-3D Finite Element System-User's Manual*. Part I, II and III, Section of Structural Mechanics, Delft University of Technology, the Netherlands.

Zuo, G., Druum, E.C. and Meier, R.W., 2007. *Environmental Effects on the Predicted Service Life of Flexible Pavements*. Journal of Transportation Engineering, 133(1), pp.47-56.