Verification of stiffness modulus of road bases and sub-bases

Christ van Gurp & Rien Davidse
KOAC•NPC, Apeldoorn and Vught, The Netherlands

ABSTRACT: The results of a study on the development and applicability of the Light Weight Deflectometer (LWD) and Falling Weight Deflectometer (FWD) for the verification of the quality of bearing capacity of road bases and sub-bases are presented. Relationships have been developed between the bearing capacity and stiffness moduli of base courses and sub-bases and the stage of completion of the road. In any pavement design assumptions are made for the stiffness moduli of all constituent layers. The stiffness of a sand sub-base for example may be set to a value of 100 MPa. After construction of this sand sub-base an LWD test may provide data on the stiffness of the layer. This stiffness will be lower than used in the pavement design. Differences in load spreading and confinement in each construction stage may be the predominant causes. A model has been developed to assess how the lower seated layers stiffen with each extra layer, both due to overburden stress and changes of load spreading. The model is easy-to-use and does not require complicated stress dependency characteristics although these characteristics have been used in the development of the tool. The model can be used to assess the current stiffness modulus but also to predict whether the targeted design stiffness will be achieved. The paper addresses the development of the tool, the use of it in quality control and the predictive accuracy.

KEY WORDS: Light weight deflectometer, stiffness modulus, road foundation, sub-base.

1 INTRODUCTION

Falling Weight Deflection (FWD) testing is commonly applied in cases where the structural condition of roads and other pavement structures approaches the end of life condition and distress is becoming visible at the pavement surface. The FWD data are used to assess the residual structural life. In combination with other data such as layer thicknesses and information on material properties decisions can be made to what extent and degree strengthening is required.

FWD testing is more and more used in performance based contracts for the assessment of the zero condition, i.e. the structural condition at the start of the contract, usually measured just after completion of the works. The test also enables the determination of the stiffness moduli of the constituent pavement layers during the construction stage. In Scotland it is obligatory to perform FWD testing at each layer and shift in construction projects on roads of the arterial network. The benefit of this approach is that already during construction information is gathered whether the realised product complies with the requirements. Nevertheless, practice shows that analysis of the collected data requires quite some engineering judgement and experience. The test data do not provide for an immediate decisive explanation whether the structure under analysis meets or does not meet the design criteria.

This paper presents the findings of a research project in which tools have been developed for a quick and simple analysis of FWD data for the assessment as to what degree the stiffness modulus of a pavement layer should grow to predict the most likely stiffness of that layer after one or more layers have been laid on top of it. The paper describes phase 1 of the project, i.e. the development of a model of the verification and prediction of the stiffness modulus of the unbound sub-base during all stages of road construction. Research on stiffness assessment of the road foundation during all construction stages is still ongoing.

2 LINEAR ELASTIC MODELLING OF PAVEMENT STRUCTURE

Most mechanistic pavement design procedures used in the Netherlands and many other countries are based on layer elastic modelling of each layer of a pavement structure. This implies that fixed stiffness moduli are assigned to each layer. Effects of load duration, temperature and stress conditions are usually accounted for by selecting appropriate characteristics values of the stiffness moduli. This approach assumes that, once a stiffness modulus has been assigned to a layer and or material, this stiffness will not change anymore in the model, even when the loading is doubled or extra layers are modelled on top of the existing layered structure. The following schematic example will show what effect this assumption brings along.

The very light blue line in the left graph of Figure 1 shows the outer deflections as measured by an FWD load of 50 kN on a sand subgrade with a stiffness modulus of 100 MPa. Three 100 mm layers of asphalt with a stiffness modulus of 7000 MPa each are schematically modelled on top of the sand subgrade. From the graph can be concluded that the tails of the deflection bowls hardly change with the increasing number of pavement layers on top of the sand layer. Backcalculation programmes commonly use these tails for a first estimate of the stiffness modulus of the subgrade and deep seated layers. In this case the tails are similar, implying that the backcalculated stiffness moduli for the sand layer will be similar as well. This implies that linear elastic modelling and backcalculation is not suited for accounting for changes of stresses in the sand sub-base and subgrade due to traffic or FWD loading and the overburden of the asphalt layers and road foundation.

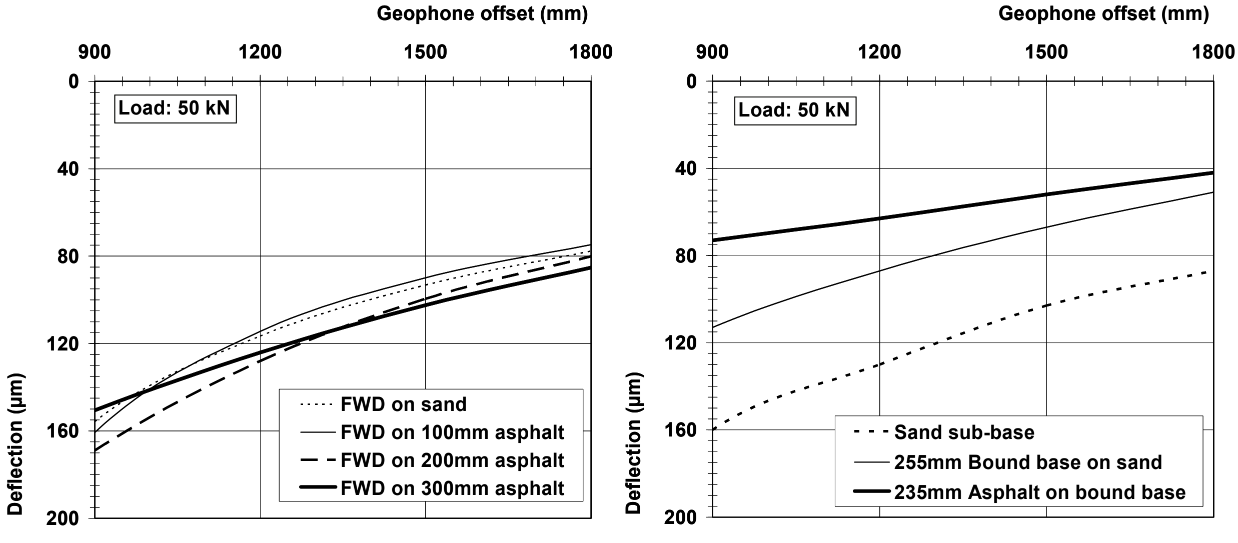

Figure 1: Tails of deflection bowls for various pavement structures

The graph on the right-hand side of Figure 1 shows the tails of the deflection bowls actually measured at three stages of construction of a motorway: at the top of the sand sub-base, at the top of the road base of AGRAC (= Asphalt granulate stabilised with cement), and at the top of the asphalt wearing course. The graph clearly demonstrates that the far field deflections decrease with increasing number of layers, pointing to an apparent stiffening of the sand sub-base and subgrade.

3 STRESS DEPENDENT STIFFNESS BEHAVIOUR

3.1 Actual response

Figure 2 gives another example of the increase of the sub-base or subgrade stiffness modulus as construction of the road approaches the final stage. The stiffness moduli backcalculated from the deflections measured prior to construction of one or more layers form the reference.

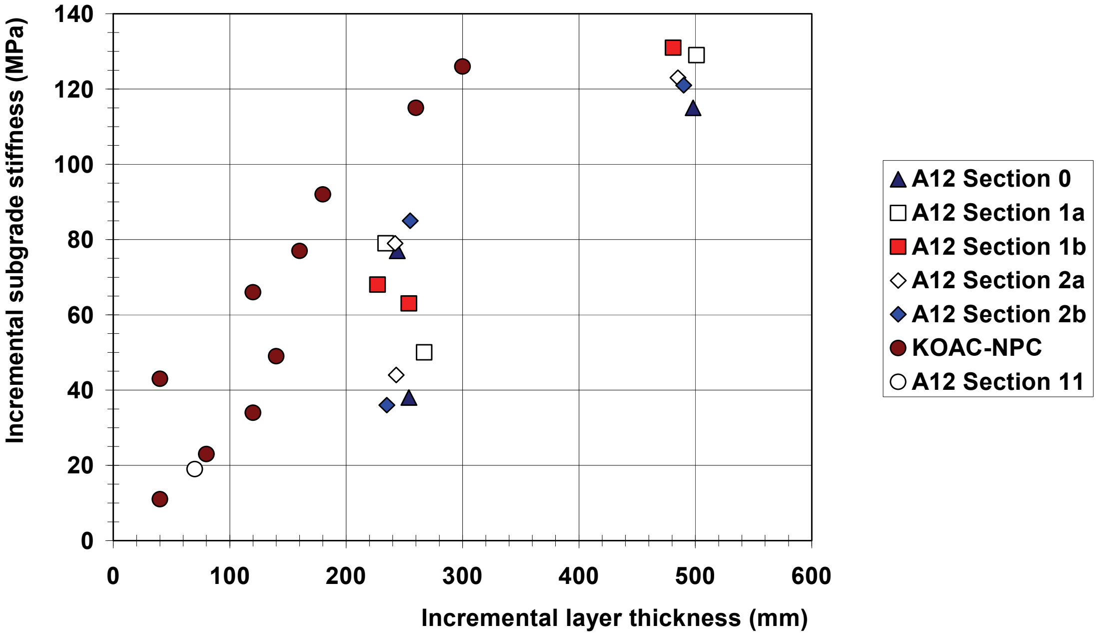

Figure 2: Actually measured increase of stiffness of sand sub-base with increasing layer thicknesses of pavement layers

For all later rounds of FWD testing, stiffness moduli of all constituent layers are backcalculated again. The change of layer thickness from the reference condition (condition prior to construction) is displayed at the horizontal axis of Figure 2; the incremental stiffness modulus of the sand sub-base is displayed on the vertical axis. The increase of layer thickness may consist of the thickness of the road foundation or the sum of the thicknesses of the road foundation and other layers.

Various reference conditions can be defined, when multiple rounds of deflection testing were performed. If three rounds were used, the data of Round #1 will form the basis for analysis of the apparent stiffening detected by the Rounds #2 and #3. The changes of layer thickness and stiffness modulus are displayed in Figure 2. Round #2 data can also serve as reference for the Round #3 data. This implies that three rounds of testing, result into three data points for the graph depicted in Figure 2, whereas four rounds of testing yield six data points.

The stiffness modulus of the subgrade can be determined by using the surface modulus inferred from deflection data directly measured on top of the subgrade. This surface modulus is calculated as follows:

$$E_{surf} = \frac{S \cdot \left(1 - \nu^2\right) \cdot F}{\pi \cdot a \cdot d_0} \tag{1}$$

Where E_{surf} = Surface modulus (MPa)
S = Loading plate rigidity factor (-)
ν = Poisson's ratio (= 0,35)
F = (Target)load in Falling Weight Deflectometer test or Dynamic Plate Bearing test (N)
a = Radius of loading plate (mm)
d_0 = Centre deflection (mm)

The loading plate rigidity factor is set to a fixed value of 2.

3.2 Explanation of increase of stiffness of sand sub-base

The in practice observed increase of stiffness modulus of the sand sub-base or subgrade with increasing number of construction layers may be due to:

- increase of dead weight of all layers on top of the sand sub-base or subgrade;
- change of confinement imposed by traffic or FWD test load;
- influence of seasonal effects;
- post-compaction densification of sand sub-base by construction of road foundation and asphalt layers.

The last of the explaining factors of influence points at a change of material properties, while the first two factors are mainly due to differences in stress conditions. Sand and all other unbound or self-hardening granular layers in a pavement structure have a stress sensitive elastic deformation response. This means that the stiffness modulus is not a constant, but a function of the combination of horizontal and vertical stresses in the sand sub-base. This stress sensitive behaviour is often expressed by the k-Theta model.

$$M_r = k_1 \cdot \left(\frac{\Theta}{\sigma_0}\right)^{k_2} \tag{2}$$

Where M_r = Resilient modulus (MPa)
Θ = Sum of principal stresses (kPa)
σ_0 = Reference stress (= 1 kPa)
k_1 = Model coefficient (MPa)
k_2 = Model coefficient (-)

The sum of the principal stresses for a point in the vertical centre line of a circular loading (e.g. FWD loading) equals the sum of the vertical stress and twice the horizontal stress. If the sum of the principal stresses is doubled, the resilient modulus will increase by a factor of 2^{k2}. From triaxial testing on sand it appears that the k_2 coefficient commonly varies between 0,48 and 0,72 with an average value of 0,60 (Huurman, 1997). This implies that doubling of the sum of the principal stresses leads to a 40% increase of stiffness modulus of sand, providing that moisture content and density do not change in the meantime.

4 DEVELOPMENT OF STIFFNESS PREDICTIVE MODEL

4.1 Influence of overburden stress and load spreading

In the research project presented in this paper, a model was developed for a quick yet accurate prediction of the change of stiffness modulus of the sand sub-base or subgrade with increasing number of layers during road construction. The model accounts for effects of changes of overburden stresses of the extra layers and changes in stress condition in the sand by enhanced loading spreading due to the dual effects of layer thickness and higher stiffness modulus of the higher pavement layers.

The incremental stiffness of the sand sub-base or subgrade is primarily due to the weight of the structural layers on top of the sand, as demonstrated by Van Gurp et al., 2010 and 2011. The extra layers lead to extra weight and consequently higher confining stresses in the sand.

The higher layers are usually stiffer than the sand sub-base, as a result of which they redistribute traffic load or FWD loading stresses over the deeper layers. How and to what extent this redistribution will take place, can be investigated by stress dependent material modelling. However, this way of data processing is far too complex for everyday practice and appears to lead to unexpected and inaccurate results in some cases. For that reason, the predictive model was chosen to fit to the standard way of mechanistic modelling. The stress dependency properties of the unbound materials were accounted for by regression analysis of sets of FWD data collected during construction of various types of roads.

4.2 Basic shape of predictive model

The basic shape of the predictive model is:

$$\Delta E_z = c_1 \cdot \Delta h_{w,eg} + c_2 \cdot \Delta h_{w,E} \tag{3}$$

Where ΔE_z = Incremental stiffness modulus of sand sub-base (MPa)
$\Delta h_{w,eg}$ = Incremental layer thickness adjusted for increase of overburden stress (mm)
$\Delta h_{w,E}$ = Incremental layer thickness adjusted for change of load spreading (mm)
c_1, c_2 = Model coefficients (N/mm^3)

The model does not predict the stiffness, but the change of stiffness. Analysis of the test data showed that prediction of an incremental stiffness modulus appeared to be a better predictor than a stiffness multiplier. The model coefficients c_1 and c_2 can be regarded as spring constants. The two types of incremental layer thickness are defined as follows:

$$\Delta h_{w,eg} = \sum_{i=1}^{NL} h_i \cdot \left(\frac{\gamma_i}{\gamma_0}\right)^{k2} \tag{4}$$

$$\Delta h_{w,E} = \sum_{i=1}^{NL} h_i \cdot \left(\frac{E_i}{E_0}\right)^{k2} \tag{5}$$

Where h_i = Thickness of layer i (mm)

NL = Number of layers above layer under analysis (-)
γ_i = Wet density of layer i (kg/m³)
γ_0 = Reference density (kg/m³)
E_i = Stiffness modulus of layer i (MPa)
E_0 = Reference stiffness modulus (MPa)
k_2 = Indicator stress dependency (-)

The first incremental layer thickness (Equation 4) accounts for the change of overburden stress; the second one for the change of load spreading due to the higher stiffness moduli over the higher layers.

The parameters γ_0, E_0 and k_2 are set to constant values, representing average conditions. The model coefficients c_1 and c_2 have been derived from regression analysis. These coefficients provide for an indication of the proportional influence of the overburden issue and the load spreading issue. For the case of sand sub-bases, $c_1 = 0.0759$ and $c_2 = 0.0162$ were found to be the best estimates. Figure 3 shows the accuracy of the predictive model. The coefficient of correlation r^2 equals 0,96 and the standard error of estimate of the incremental stiffness of the sand sub-base appears to be 16 MPa.

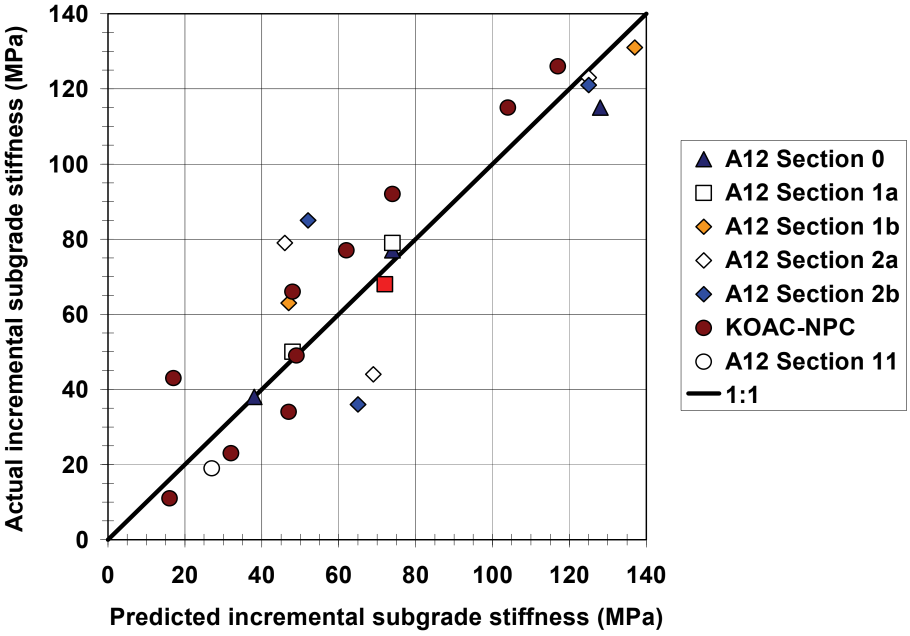

Figure 3: Test of predictive accuracy of model for assessment of incremental stiffness of sand sub-base due to structural layers on top of it

5 APPLICATION OF PREDICTIVE MODEL

5.1 Estimation stiffness modulus of sand sub-base

The applicability of the model is demonstrated by the following three layer example. The subgrade consists of sand. The FWD deflection data computed on top of the sand form the reference. To complete the construction of the road a total of 150 + 300 = 450 mm of layers will be placed on top of the sand subgrade (see Table 1).

Table 1: Material properties of pavement structure in example

Material	Layer thickness (mm)	Stiffness modulus (MPa)	Wet density (kg/m^3)
Asphalt	150	7000	2300
Road foundation	300	400	1900

The incremental layer thicknesses adjusted for increase of overburden stress and change of load spreading appear to be 501 mm and 2609 mm (see Equations 4 and 5). The model computes an incremental stiffness modulus of 80 MPa for this sand subgrade. In practice FWD testing directly on the subgrade usually results in sand subgrade stiffness moduli in the range of 50 to 70 MPa. After placing the last asphalt layer, the stiffness modulus of the subgrade should thus have grown to a value of 130 to 150 MPa. If a value of 100 MPa was used in the design of the pavement structure, the FWD verification and use of the predictive model show that the subgrade will most likely meet the design requirement.

The predictive model can also be used in the opposite direction. Suppose that we need a minimum value of 100 MPa for the sand subgrade during the service life of the pavement. In that case the minimum value of the subgrade stiffness modulus to be measured on site should amount at least 100 - 80 = 20 MPa. This test level can be measured quite simply by a Light Weight Deflectometer (LWD) (see Figure 4).

Figure 4: Light Weight Deflectometer test

The handheld computer of the LWD may compute the surface modulus of each drop during testing. The surface modulus measured directly on the subgrade is more or less equal to the stiffness modulus normally used in design calculations. For LWD tests on the road foundation and asphalt layers, this assumption no longer holds. The surface modulus will be higher to much higher because of the increasing influence of the thick and stiff layers higher in the pavement structure.

However, it would be very handy during on site assessment of the quality of the bearing capacity of structural layers to express the bearing capacity in terms of surface moduli. A modified version of the predictive model was developed to facilitate use of that surface modulus.

5.2 Estimation of surface modulus

Equation 1 shows how the surface modulus is computed. This surface modulus is in this case based on the centre deflection. For the example pavement structure of Table 1 the corresponding surface modulus at the top of the asphalt layers will equal 531 MPa if the sand subgrade under the road foundation has a stiffness modulus of 100 MPa.

Figure 5 shows that the incremental layer thickness adjusted for load spreading and stiffness alone is already a good indicator of the increase of surface modulus with increasing number of layers. Equation 6 presentst the regression equation. The combination with the incremental layer thickness adjusted for overburden stress provides for almost equal predictive accuracy.

$$\Delta E_{z,surf} = 0.282 \cdot \Delta h_{w,E} \qquad (6)$$

Where $\Delta E_{z,surf}$ = Incremental surface modulus of sand sub-base (MPa)

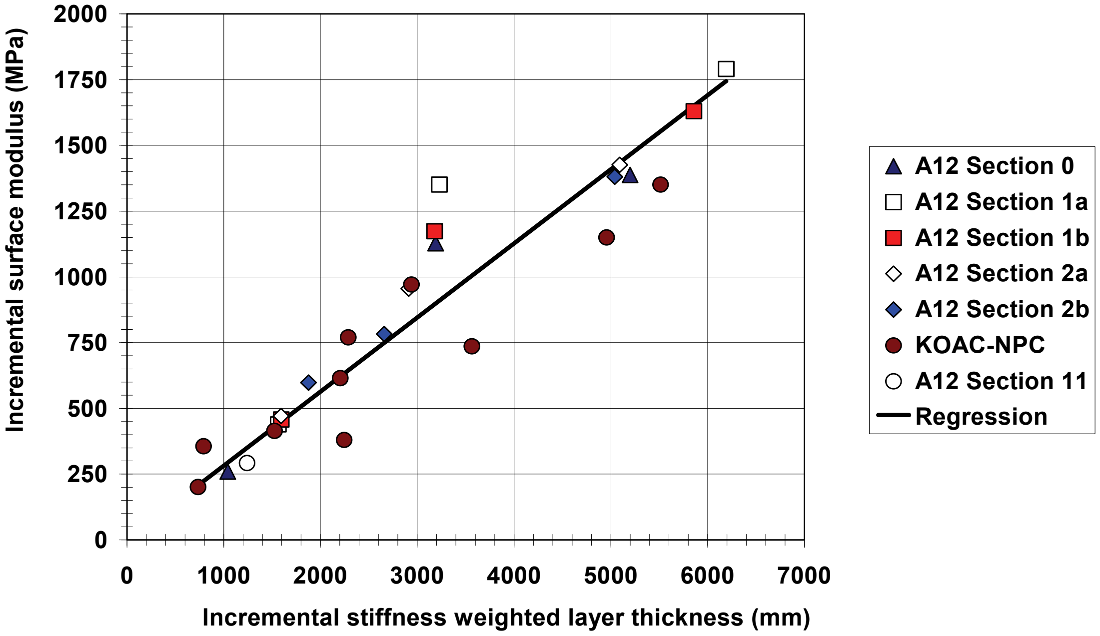

Figure 5: Increase of surface modulus as function of incremental layer thickness adjusted for stiffness

The layer thicknesses 150 mm and 300 mm of the example of table 1, result into the values of 1919 mm and 689 mm for the stiffness weighted layer thicknesses. With the help of equation 6 and figure 5 can be derived that the incremental surface modulus will be 735 MPa. This implies that for the case of a surface modulus of 50 MPa measured directly on the sand subgrade, deflection testing at the asphalt pavement surface should result in a minimum surface modulus of 785 MPa.

6 CONCLUSIONS

This paper shows how the weight, thickness and stiffness of the layers on top of a sand sub-base or subgrade affect the stiffness modulus of that sub-base or subgrade. An easy-to-use model has been developed to quantify this effect and to use the relationships found for prediction and verification of stiffness during the construction of a road.

The degree to which the stiffness modulus of a sand sub-base or subgrade apparently increases during construction can be estimated after the completion of the road pavement structure from measurements of layer sthickness, density and stiffness modulus of each structural layer and even per individual asphalt layer.

The model presented in this paper is a handy tool for use in performance based contracts where the contractor has to show whether the structural properties of the lower layers of the pavement structure will comply with the design assumptions made for the whole pavement structure. Non-destructive testing on a completed pavement structure may provide accurate data on this issue as well, but is scheduled far too late if remedial activities at the sub-base and road foundation cannot be avoided. The approach outlined provides an idea of the quality of the work realised during construction. The results of this verification tool provide the contractor and commissioner with more confidence whether the final construction may deliver the expected result.

The predictive model equations can be written in an easy-to-use Excel spreadsheet, facilitating quick analysis in practice. The model can be applied for setting target stiffness modulus values for the sand sub-base or subgrade that must be attained during the different construction stages.

For enhancement of the applicability of the stiffness predictive model, an analogue approach has been used with the surface modulus as target variable. This variable can be measured on site and can be determined more easily than layer stiffness moduli.

REFERENCES

Huurman, M., 1997. *Permanent deformation in concrete block pavements*. PhD thesis, Delft University of Technology, Delft, The Netherlands.

Van Gurp, C.A.P.M., Cillessen, R. and Blom, S., 2010. *The use of LWD on granular bases and asphalt structures*. Paper 6th European FWD Users Group Meeting, Belgian Road Research Centre, Sterrebeek, Belgium.

Van Gurp, C.A.P.M. and Blanken, A., 2011. *Verification of stiffness of road bases* (in Dutch). CROW Infradagen 2012, CROW, Ede, The Netherlands.