The Influence of Groundwater Level on the Structural Behaviour of a Pavement Structure Using FWD

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ABSTRACT: The effect of groundwater table level on the structural response of an instrumented flexible pavement in southern Sweden was studied using multilevel Falling Weight Deflectometer (FWD) testing. In order to raise the groundwater table level under the pavement structure, the outlets of the pavement's subsurface drainage system was blocked for three months. Thereafter, it was unblocked, allowing the pavement to recover to its normal draining condition. During this period, variations in the groundwater level and subsurface volumetric moisture content were registered. Manipulation of the drainage system significantly affected the ground water level and the pavement unbound layers moisture conditions. Both the granular layer and the subgrade stiffness significantly decreased with increasing moisture content. In all the FWDs performed, the granular materials exhibited stress-hardening behaviour. However, the subgrade showed stress-softening response in unsaturated condition and stress-independent behaviour in saturated state. In an attempt to determine the $k-\theta$ model parameters from the backcalculated internal stresses and unbound layers moduli, it was observed that the k_1 parameter decreased with increasing moisture content for both the granular layer and the unsaturated subgrade materials.

KEY WORDS: Bearing capacity, Falling Weight Deflectometer, stiffness, backcalculation, drainage, groundwater table, moisture content.

1 INTRODUCTION

Drainage is one of the important elements in the design of pavement structures, minimizing the detrimental effects of water on roads performance. In unbound pavement materials and subgrade soils, moisture presence decreases their resilient modulus (Cary and Zapata, 2011) and increases their rate of permanent deformation (Erlingsson, 2010). Prolonged presence of excess moisture content can significantly accelerate pavement deteriorations and reduce the service life of the road network.

In recent years, due to the growing trucking industry demands, both the number and weight of the axle loads have increased. This affects the rate of distresses and damage caused to pavements due to traffic loading which is accelerated when accompanied with presence of excess moisture. Therefore, more attention should be paid to drainage condition and its influence on the road performance and bearing capacity, especially in thin pavement structures.

The county road 126 is a two-lane two-directional rural road in southern Sweden. Since the opening of this road section to traffic in 1985, a stretch of the road near Torpsbruk, exhibited unexpectedly rapid deteriorations in form of low bearing capacity, rutting and cracking. Investigations revealed that the problem has been evidently due to prolonged exposure of the section to high groundwater flow under the pavement, originated from a nearby hill with wet ground conditions. Therefore, in a research project and in order to lower the groundwater level, 250-m long stretch of the road was enhanced with subsurface drainage system. The drainage was a prefabricated vertical drain, consisting of synthetic polymer core with geotextile filters and longitudinal bottom collective pipes (Bäckman, 1986). This section was further equipped with subsurface volumetric moisture content and groundwater level probes in 2009.

A study on investigating the effect of groundwater table level in unbound layers moisture contents and its consequent effect on the structural response of the pavement was performed at this section. The groundwater table level under the pavement section was changed by manipulating the drainage system for three months in summer 2011. During this period, variations in the groundwater level and subsurface volumetric moisture contents were registered using the instrumentations. The mechanical behaviour of the pavement with regards to changes in moisture condition was studied by conducting frequent Falling Weight Deflectometer (FWD) testing with multi-level loads. The stress sensitivity of the unbound layers was studied by backcalculating the FWDs deflection data. The field data measurements and the analyses of the data are presented in this paper.

2 EXPERIMENTAL PROGRAM

2.1 Testing Procedure

The field measurements were divided into two major phases: the draining phase in which the drainage was functioning (unblocked outlets), and the non-draining phase in which the drainage was not functioning (blocked outlets). Figure 1 shows the variation in groundwater level during the study period measured by the six groundwater rods across the test road.

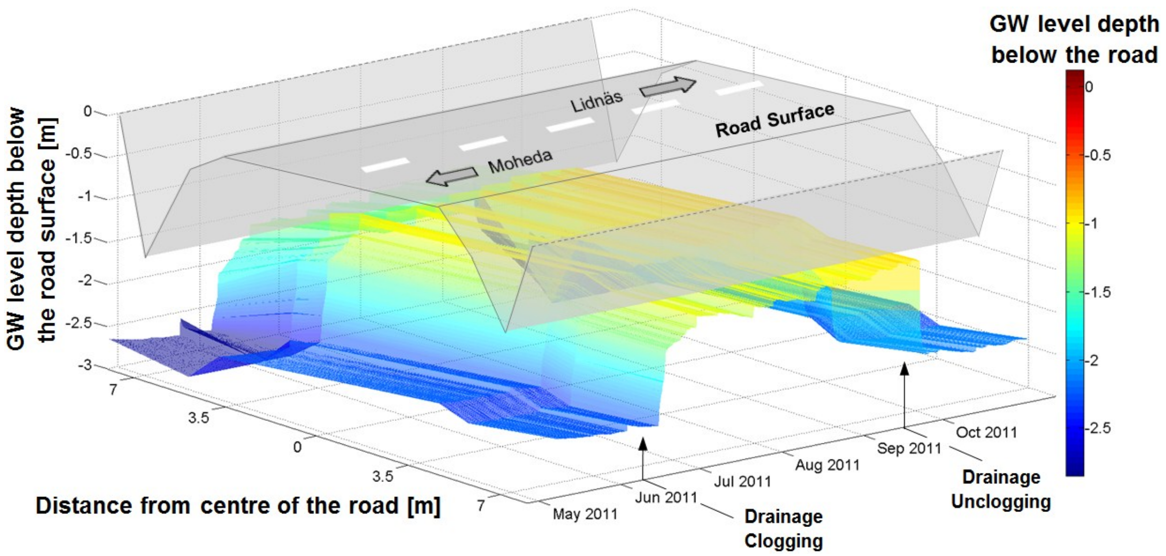

Figure 1: Variation of the groundwater table level due to drainage manipulation.

The drainage outlets on both sides of the road were blocked on 7 June 2011, which resulted to groundwater raise from 2.5 m to approximately 1.0 m below the road surface. The section was kept in this condition for more than three months, until the outlets were unblocked on 15 September. Shortly after unblocking the drainage outlets, the groundwater level dropped back to normal draining level.

2.2 Test Site Pavement Structure

The pavement was a conventional three layer flexible structure consisting of 100 mm Hot Mix Asphalt (HMA) layer, 160 mm crushed gravel base layer and 300 mm natural sandy gravel subbase layer with sandy silt subgrade soil. The HMA layer was a dense graded mix with 16 mm maximum grain size and bituminous binder (pen 160/220).

2.3 Test Site Instrumentation

The depth to the groundwater table level and the volumetric moisture contents in unbound layers were the influencing environmental factors in this study. The groundwater level was monitored by the six probes that were installed across the test section. Two different sensor brands (Druck on eastern and Keller on western side of the road) with separate automatic data logging systems were used. They both consisted of pressure cell sensors in PVC pipes and were identical in principal.

The volumetric moisture content in unbound layers were measured from two moisture rods each consisting of four high frequency-domain capacitance probes mounted at 0.5, 0.9, 1.2 and 1.5 m depths (EnviroSMART probe from Campbell Scientific), that were installed on the eastern side of the road. The moisture rods were installed along the unpaved shoulder of the road with automatic data logger. Schematic overview of the test site instrumentation is illustrated in Figure 2.

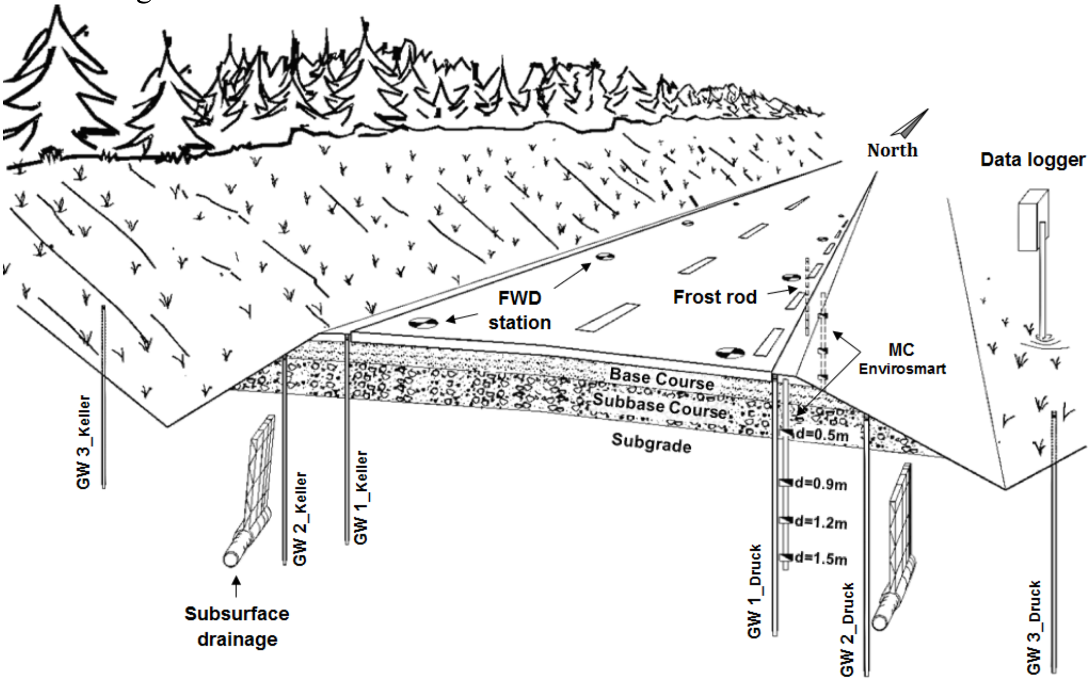

Figure 2: Test site instrumentation (GW: groundwater and MC: volumetric moisture probes).

2.4 FWD Testing and Sequence

The KUAB trailer mounted FWD device, which produces an impulse force using a combined two-mass and buffer system, was used for the structural assessment of the pavement system.

All of the FWD tests were performed two times and at 30, 50 and 65 kN load levels. Deflections were measured at 0, 0.2, 0.3, 0.45, 0.6, 0.9 and 1.2 m distance from the centre of the loading plate which was 0.15 m in radius. For each load level, the average value of all the selected FWD stations was used as the representative deflection basin for the test section at that load level.

In total, 11 series of FWD measurements were performed. One FWD test was conducted on 11 May before the drainage blocking. Five FWD tests were performed during the non-draining condition when the drainage was blocked (13 and 20 June, 4 July, 1 August and 14 September), and five after the drainage unblocking on 16, 19, 22 and 26 September and 13 October.

The FWD tests were conducted along the outer wheel path of the road in both directions with 10 m intervals between the stations (Figure 2). For this study, FWD data from 8 stations (4 at each direction) which were closest to the moisture probes were used. FWD tests conducted on 11 May and 13 June had a different setup. They consisted of 11 stations with 2 m intervals, performed only in one direction close to the moisture probes.

3 FWD DEFLECTIONS AND MOISTURE MEASUREMENTS

Figure 3 shows volumetric moisture content variations in the pavement unbound layers due to changes in the groundwater table level. The pavement structures volumetric moisture content shown in this figure is measured by the eight probes installed along the two moisture rods. Figure 3 shows that the moisture contents in the unbound layers were consequently affected by groundwater changes due to drainage clogging.

The maximum FWD deflection corresponding to 50 kN load level is also shown in Figure 3. The significance of the drainage system in reducing the unbound layers moisture content and its effect on the pavement overall stiffness is pronounced in this figure.

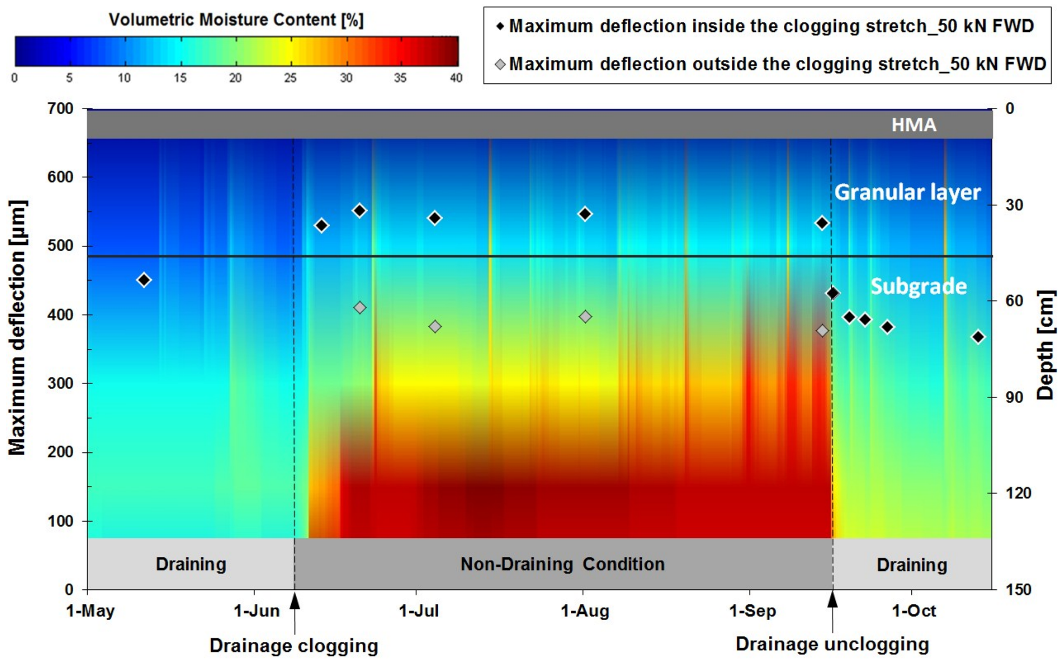

Figure 3: Subsurface volumetric moisture content variation in unbound layers due to drainage blocking and maximum deflection corresponding to 50 kN FWD.

Shortly after the drainage clogging, volumetric moisture content in the lower subgrade levels (1.50 and 1.20 m depth) increased rapidly from 15% to more than 35%. In the granular layer, moisture content measured at the bottom of the subbase layer increased from 8% to nearly 15%, which was mainly due to capillary moisture increase. Increase in the groundwater table level from 2.5 to 1.0 m below the pavement surface increased the maximum 50 kN FWD deflection by 36 %. The average maximum deflection for 50 kN load in the draining condition was about 396 microns. In the section with blocked drainage (non-draining condition), this value was increased to 541 microns.

Shortly after unblocking the drainage pipes on mid-September, volumetric moisture content in the unbound layers reduced to values slightly higher than that of the pre-clogging. This rapid response could be explained by the sandy silt nature of the subgrade soil in the section and the efficiency of the drainage system. The slightly higher volumetric moisture contents was due to generally moister ground conditions in autumn compared to late spring which was mainly due to more rain events, also observed in the preceding years measurements.

4 BACKCALCULATION OF LAYER MODULI

The computer program Evercalc (Everseries, 2005) was used for backcalculating pavement layers moduli from the FWD deflection data. In the backcalculation, the pavement structure was modelled as a four layer system consisting of a 100 mm thick HMA layer underlain by a 460 mm thick granular layer. Since the base and subbase were relatively thin with similar material properties they were modelled as a single layer (Irwin, 2002). The subgrade which was a sandy silt material was 2.5 m thick with an infinite stiff bedrock bottom layer (3500 MPa). In the backcalculation, the modulus of the HMA layer was modified by the mid-depth temperature measured during the FWD tests (Everseries, 2005). A Poisson's ratio of 0.35 was assigned to HMA, granular and the bedrock stiff layer. For the subgrade layer Poisson's ratio of 0.4 was assumed. The backcalulation flowchart used in Evercalc and the algorithm used to determine materials stress dependency (discussed further) is shown in Figure 4. In all the backcalculations, the RMS convergence error was less than 3%.

The stress dependency of the unbound layer materials were studied by backcalculation of the FWD three load levels deflection data. In non-destructive testing of pavement materials, this is usually achieved through adjusting the layer moduli in an iterative manner using different constitutive stress modulus relationships (Salour and Erlingsson, 2013).

In this study, the so-called $k-\theta$ universal constitutive equation, expressed as below, was chosen (ARA, 2004):

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a}+1\right)^{k_3} \qquad \textbf{(1)}$$

where M_R= resilient modulus, θ=bulk stress, p_a =normalizing stress or atmospheric pressure (here chosen as 100 kPa), k_1 , k_2 and k_3 are dimensionless regression constants and $\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}$ = octahedral shear stress.

In this model, the parameter k_1 is directly proportional to resilient modulus and is therefore positive. Since increase in bulk stress results in stiffening effect in unbound granular materials, k_2 parameter also has a positive sign. In contrast to bulk stress, increase of shear stresses in fine grained soils results in softening effect and therefore k_3 has a negative sign.

Along with the backcalculation of the layer moduli for each load level, internal stresses in the unbound layers were also backcalculated. For the granular material, middle of the granular layer and for the subgrade material, top of the subgrade layer were chosen to represent the stress state. Using the backcalculated moduli and internal stresses at the stress points as inputs to the constitutive model, the model parameters were determined through curve fitting in Matlab (Figure 4).

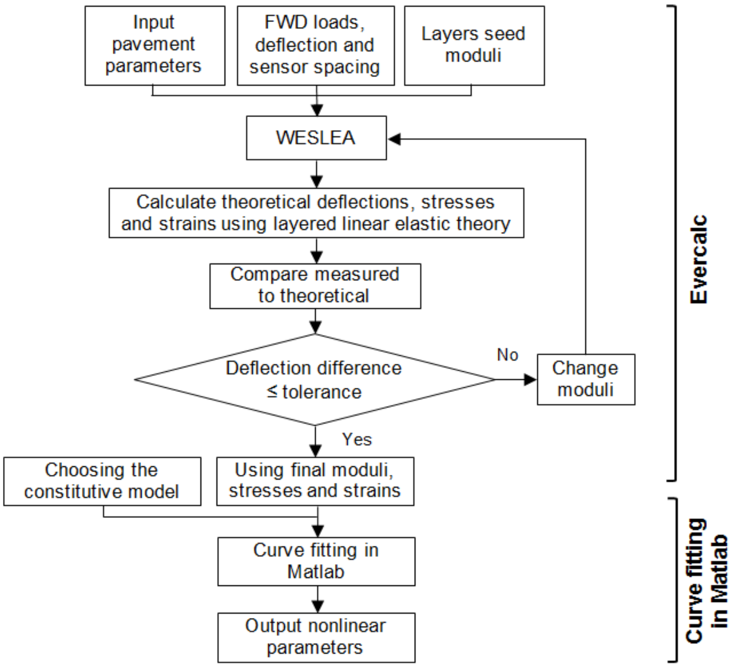

Figure 4: Backcalculation of layer moduli and nonlinear parameters algorithm.

4.1 Granular Layer

The backcalculated granular layer stiffness and the volumetric moisture content measured at 0.5 m depth is presented in Figure 5. In this figure, spikes in the moisture measurements were due to rapid changes in granular layers moisture content caused by precipitation events (note that the moisture rods were installed along the unpaved shoulder of the pavement). The impact of moisture on the granular layer stiffness and its stress dependency can be seen in this figure. In the granular layer, moisture increase due to drainage clogging resulted in approximately 38% reduction in stiffness. The backcalculated 50 kN stiffness decreased from 230 MPa to 153 MPa after the drainage was clogged (non-draining condition). In all the FWD performed, higher stiffness for the granular material were backcalculated as the FWD load level increased, representing the stress hardening behaviour of the granular materials.

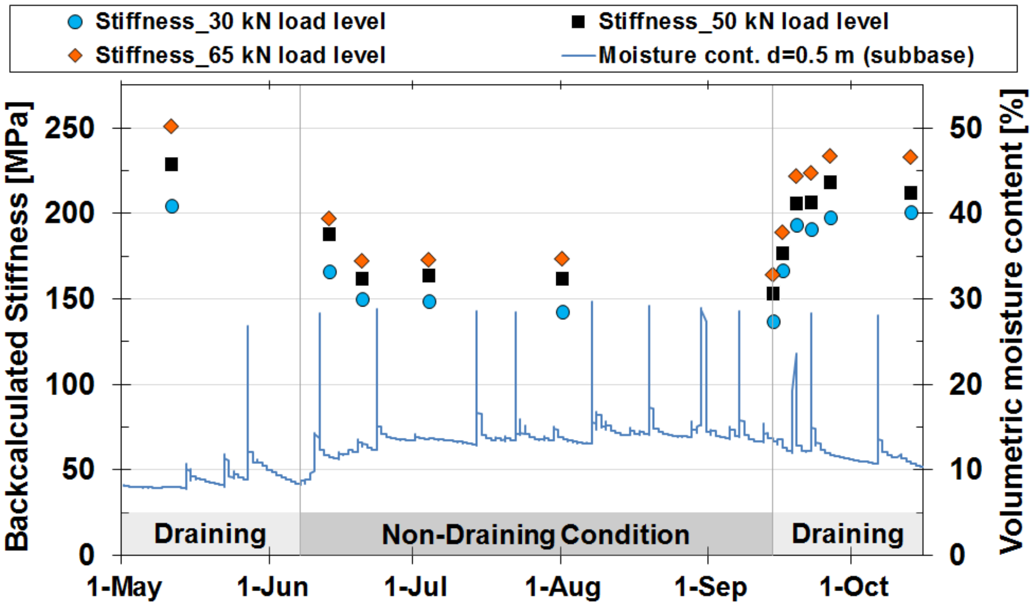

Figure 5: Backcalculated granular layer moduli to multiple loads and volumetric moisture contents measured near the bottom of the subbase (depth = 0.5 m).

In unbound granular materials, the simplified k-θ model in which k_3=0 often adequately captures its overall stress dependency (first stress invariant) under compressive field loading conditions (Rada and Witczak, 1981).

The backcalculated stiffness of the granular layer during the study period increased with increasing load level (Figure 5). This was in agreement with the general stiffening behaviour of granular materials where increase in bulk stress results in material hardening (k_3=0) (Gomes Correia, 2004). Therefore, the simplified model was chosen for the granular material.

Based on the goodness of fit in the regression process and the literature, k_2=0.35 was selected for the granular layer (Meshkani et al., 2003). An experimental study on moisture sensitivity of unbound granular materials using repeated triaxial testing, by Rahman and Erlingsson (2012) showed that k_2 parameter is almost independent of the moisture content.

It was observed that, volumetric moisture increase from 8.0% measured on 11 May to 15.0% measured on 4 July, corresponded to a k_1 decrease from 2389 to 1770 (26% decrease). The variation in the k_1 parameter for granular layer with volumetric moisture content changes due to drainage clogging is shown in Figure 7.

4.2 Subgrade

The backcalculated subgrade stiffness and volumetric moisture registrations at 0.9, 1.2 and 1.5 m depths are shown in Figure 6. Similar to the granular layer, the subgrade stiffness significantly decreased as the moisture increased. During the draining condition (unblocked drainage) the backcalculated 50 kN subgrade stiffness was nearly 157 MPa. When the drainage was blocked (non-draining condition) the subgrade decreased to 99 MPa (37% reduction). The subgrade response behaviour to multilevel loads during the study period can be divided into two phases: the draining phase in which the drainage was functioning and the subgrade was in unsaturated state, and the non-draining phase in which the drainage was not functioning and the subgrade was in saturated or nearly saturated state.

In all the FWD tests conducted during the draining phase, the subgrade exhibited stress-softening behaviour (k_3<0). Lower stiffness values were backcalculated for subgrade material as the FWD load level increased.

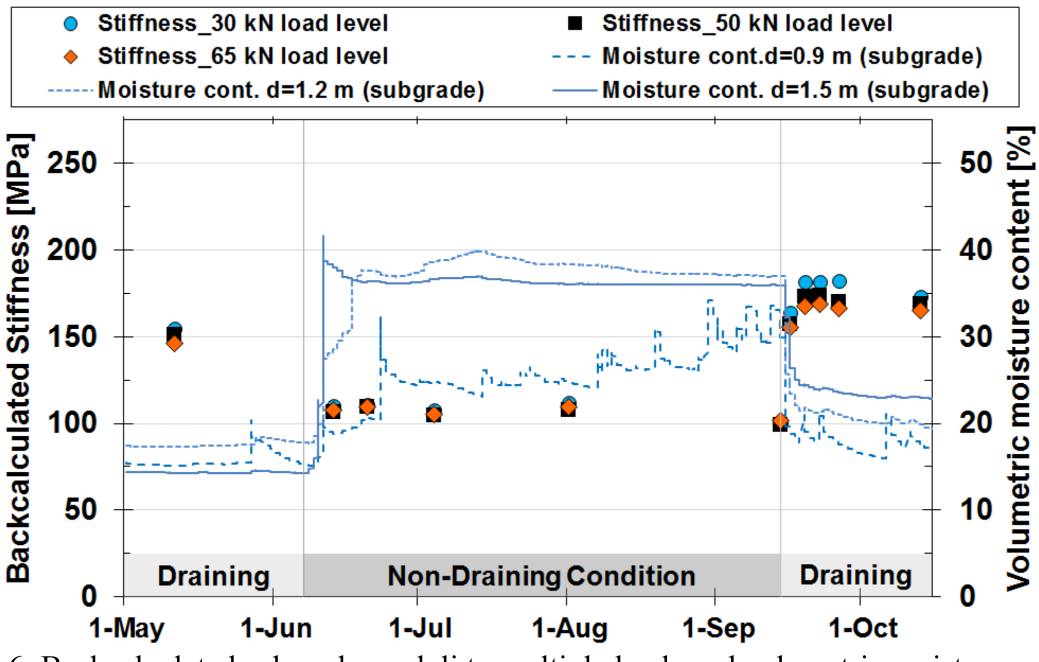

Figure 6: Backcalculated subgrade moduli to multiple loads and volumetric moisture contents measurements.

However, the subgrade stiffness in non-draining condition, when the subgrade was in saturated state, remained constant regardless of the FWD load level (k_2=k_3=0). This can be explained by the well-known behaviour of fine grained soils in undrained condition. The strength of the soil is a function of its effective stress. Since the effective stress in undrained condition remains constant during fast load pulses regardless of the magnitude of the deviator stress (FWD load pulse $\leq$40 millisecond), identical stiffness were backcalculated for all the FWD load levels.

In the measurements performed during the draining phase (unsaturated state), the stress-softening model in which the (k_2=0) was used. Similar to the discussion for the granular layer and the response of the subgrade to multilevel loading in unsaturated condition, k_3= -0.1 was assigned to the subgrade material (Meshkani et al., 2003) when determining the variations in k_1 parameter to moisture content changes. As can be seen in Figure 7, changes in subgrade volumetric moisture condition due to drainage blocking resulted in k_1 reduction from 1484 to 987 (34% decrease).

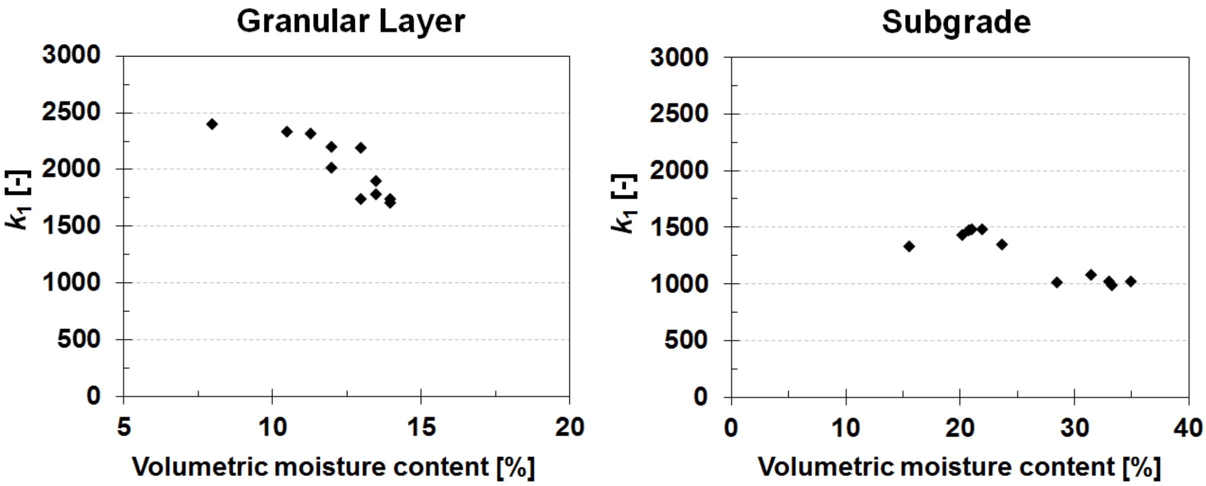

Figure 7: The parameter k_1 versus the volumetric moisture content for granular layer (left) and subgrade (right).

5 GROUNDWATER INFLUENCE ON THE PAVEMENT PERFORMANCE

Pavement performance evaluation is usually done using transfer functions for HMA fatigue cracking and subgrade rutting. The two critical strains that are traditionally considered for pavement structure evaluations are: the tensile horizontal strain at the bottom of the HMA layer (accounting for fatigue cracking), and the vertical compressive strain at the top of the subgrade (accounting for rutting). The Swedish Traffic Administration design code (TRVK Väg, 2011) accounts for the fatigue and rutting life of the pavement using the following equations. For the fatigue cracking, Equation 2, expressed as below is used:

$$N_{bb} = f_s \frac{2.37 \cdot 10^{-12} \cdot 1.16^{(1.8 \cdot T + 32)}}{\varepsilon_{bb}^4} \quad \textbf{(2)}$$

in which N_{bb} = number of Equivalent Single Axle Loads (ESAL) to fatigue failure, f_s = correction factor for existing cracking in the bituminous layer (f_s = 1.0 for new structures), ε_{bb}= horizontal tensile strain at the bottom of the bituminous layer (in microstrain) and T = temperature of the bituminous layer in degrees centigrade.

For rutting, Equation 3 is used:

$$N_{te} = f_d \frac{8.06 \cdot 10^{-8}}{\varepsilon_{te}^4} \quad \textbf{(3)}$$

where N_{te}= number of ESALs to rutting failure, f_d = correction factor for excessive moisture in the subgrade materials and ε_{te}= vertical compressive strain at the top of the subgrade (in microstrain).

The influence of the groundwater table level on the remaining fatigue and rutting life of the pavement structure was investigated. Using the FWDs data, the pavement structure's critical strains (ε_{bb} and ε_{te}) were backcalculated. The two different conditions; when the groundwater table was 1.0 m below the road surface (blocked drainage) and when the groundwater table was 2.5 m below the road surface (unblocked drainage) were considered.

The average backcalculated tensile strain at the bottom of the HMA layer (ε_{bb}) in the draining condition was 245 µm/m. This value increased to 329 µm/m with raised groundwater table during clogged drainage period (34% increase). Using Equation 2 for determining remaining life with respect to the fatigue cracking (f_s = 1.0 and T = 10 ºC) resulted in 1.09 million ESALs in draining condition (unblocked drainage) and 0.34 million ESALs in non-draining condition (blocked drainage). This corresponds to 69% reduction in fatigue life due to groundwater level condition.

For the rutting failure, compressive strain at the top of the subgrade (ε_{te}) was backcalculated. The average compressive strain in the draining condition was 254 µm/m which increased to 387 µm/m as the groundwater level raised (52% increase). Using Equation 3 for determining remaining life with respect to the rutting resulted in about 19 million ESALs in draining condition (unblocked drainage). This value was reduced to 3.6 million ESALs in non-draining condition (blocked drainage), corresponding to 81 % reduction due to drainage condition. It appears that the evaluation of surface rutting based on only subgrade vertical strain might have resulted in highly overestimating values which is the drawback of this procedure. It would be more reasonable to determine the rutting considering all the layers accumulated permanent deformation. Nevertheless, reduction in rutting life due to change in drainage condition was significant.

6 SUMMARY AND CONCLUSIONS

In an instrumented flexible pavement structure with subsurface drainage, the effect of groundwater level in the structural response of the pavement was investigated by conducting FWD tests with multilevel loads. The drainage system outlets were blocked for three months allowing the groundwater level to rise. Thereafter, the outlets were unblocked allowing the groundwater level to reach its previous condition. During this period, variations in the groundwater level and subsurface volumetric moisture contents were registered. Using the FWD data, the layer moduli of the unbound layers were backcalculated and their stress dependency and moisture sensitivity were studied. The major findings from the study were:

- Manipulation of the drainage system significantly affected the ground water level and unbound layers moisture condition.
- Groundwater table level had a significant effect on the overall bearing capacity of the pavement structure and the stiffness of the unbound layers.
- Raising the groundwater table considerably decreased the backcalculated stiffness of the granular layer and the subgrade in the pavement.
- In all the FWD tests with multilevel loads, the unbound granular layer exhibited a stress-hardening response.
- The subgrade soil showed a stress-softening behaviour in unsaturation state and stress-independent stiffness behaviour in fully saturated state to FWD tests with multilevel loads.

- Using the field data as an input to the k-θ constitutive model, it was observed that the k_1 parameter decreased with increasing moisture content in both the granular layer and the unsaturated subgrade.
- The drainage condition (groundwater level) significantly affected the pavement performance with respect to fatigue cracking and rutting criteria.

Use of multilevel load FWD measurements, as proposed here, might be a useful practice in determining pavement unbound materials stress dependent behaviour. It captures the pavement structure in-field conditions and overcomes the complications involved in conducting triaxial testing at high moisture contents. Further studies and evaluations on different pavement structures, materials and conditions are recommended.

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