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MODELLING THE NON-LINEAR BEHAVIOUR OF PAVEMENT LAYERS (SUBGRADE) USING A LINEAR ELASTIC APPROACH

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Abstract

An important aspect that needs consideration in the modelling of a pavement structure is the non-linearity of the subgrade. Pavement modelling needs to be done accurately in order to analyse the behaviour of the pavement and to determine the material properties that will be used in the mechanistic analysis calculations. Ullidtz [1983] stated that a small error in the determination of the subgrade modulus could lead to large errors in the effective elastic moduli of the other layers. The non-linearity of the subgrade is accurately accounted for by the following two methods:

- non-linear backcalculation techniques based on a finite element approach and/or programs [Rohde et al, 1992], and
- non-linear backcalculation procedure by means of the Multi-Depth Deflectometer (MDD) approach [Horak, 1986].

Traditionally subgrade stiffness is defined by a semi-infinite layer thickness (linear elastic modelling), which made it difficult to account for the non-linear behaviour of the subgrade. In order to simulate pavement response under such conditions the subgrade is represented by an "average" modulus. This modulus will usually be higher than the actual value at the top of the subgrade and lower than actual in depth to achieve balance. The most vulnerable point in the subgrade is at the top of the subgrade, where the effective elastic modulus is normally the lowest. By introducing a semi-infinite layer of a high modulus ("rigid layer") in depth, a more accurate representation of the actual effective elastic moduli can be simulated [Rohde et al, 1992; Jordaan, 1994]. An improvement or minor deviation to the linear elastic approach is thus to use a "rigid layer" approach instead of a semi-infinite layer, which accounts for changes in the subgrade stiffness. The aim of this paper is to demonstrate that by using a linear elastic approach and other techniques (subdivision of the subgrade layers), the non-linearity of the subgrade may be accurately simulated and/or accounted for.

1. INTRODUCTION

The South African Mechanistic Design Method (SAMDM) (Theyse et al, 1996 and Jordaan, 1994) developed since 1982 is well established and has been used by most road designers for pavement and rehabilitation design purposes. The method has been used extensively by researchers for new pavement designs and for refinement of existing designs as well as by engineers for practical applications (Freeme et al, 1982). The current method of mechanistic analysis / design used in South Africa has been developed largely from the results of extensive Heavy Vehicle Simulator (HVS) testing on South African roads and is based on the non-hereditary aspects of linear elastic stress / strain theory. Most of the theoretically based pavement rehabilitation design methods that have been developed to a stage where practical implementation is possible have been based on linear elastic theory. Reasons for the preference of engineers towards this theory include (Jordaan, 1994):

- Linear elastic theory is a relatively simple approach compared to some other mathematical models and lends itself to practical implementation,
- The mathematical characterisation of the pavement, as required by linear elastic theory, is relatively simple,
- Various computer programmes based on linear elastic theory have been developed and are generally available,
- Research (Monismith et al, 1967, Brown and Pell, 1967, Dehlen and Monismith, 1970) has shown that linear elastic theory (with some limitations) can be used to give an acceptable estimate of expected pavement behaviour, and
- The computer time and thus costs, required by programmes based on linear elastic theory are considerably less than those required by programmes based on other theories.

2. ASSUMPTIONS INCORPORATED IN THE LINEAR EALTIC THEORY (JORDAAN, 1994)

A mathematical model usually only gives an approximation of actual behaviour. The limitations associated with any one model depend on the type of assumptions that form the basis of the model. Therefore, an understanding of the assumptions associated with the linear elastic model would also provide an indication of its limitations. The discussion on the basis of derivation of the linear elastic model by Nair and Chang (1973) gives a good background to the understanding of its limitations (Jordaan (1988, 1994)).

The basic material properties of linear isotropic elastic equations used to calculate pavement response for evaluation through the application for an applicable failure theory are the modulus of elasticity (E-moduli) and the Poisson's ratio (μ). It is assumed that in linear elastic theory that the stress at any point within the pavement system is a linear function of the strain at the point. The modulus of elasticity (E-moduli) and the Poisson's ratio (μ) are the two independent elastic constraints through which the stresses and strains in a linear elastic system are linearly related. Therefore, fundamental to the use of a design method based on a theoretical approach derived from the linear elastic theory, is the accurate characterisation of the materials within the existing pavement in terms of the modulus of elasticity (E) and the Poisson's ratio (μ) (Jordaan, 1994). The elastic modulus or modulus of elasticity used in this paper refers to the effective elastic modulus, i.e. the modulus measured under a dual wheel load of 40 kN (corresponding to an axle load of 80 kN) (de Beer et al, 1997). The term "effective" is also used to distinguish between the elastic moduli measured in the laboratory from those determined indirectly in-situ with the Multi Depth Deflectometer (MDD) system or backcalculated from field measured surface deflection basin measurements (Freeme et al, 1982, Horak, 1986 and de Beer et al, 1988). Since the linear elastic theory presents a mathematical idealisation of natural in-situ pavement reaction, methods developed on the basis of this (or any other) theory should be verified against actual pavement reaction (Jordaan (1988, 1994)).

The assumptions applicable to the linear elastic theory as applied to the analysis of pavement response and used for the prediction of pavement behaviour are summarised as follows (Barksdale and Hicks (1973) and Burmister (1943)):

- the material in each pavement layer is linear elastic, isotropic and homogeneous,
- the behaviour of the pavement is a function of pavement reaction in terms of stress and strain as determined by linear elastic theory,
- the influence of moisture and temperature on the reaction of the pavement system in terms of stress and strain is constant,
- the surface loading on a pavement structure can be represented by vertical stress, uniformly distributed over one or more circular areas,
- the pavement is adequately characterised by a modulus of elasticity, Poisson's ratio and thickness of each layer (final subgrade layer taken as semi-infinite),
- the elastic properties of the materials within the pavement system are not stress dependent, i.e. they remain constant with variation in stress conditions,
- each pavement layer is continuously supported by the layer beneath,
- the interface conditions between layers can be considered as either perfectly smooth or perfectly rough,
- inertia forces within the pavement system are negligible, and
- the stress at a point within a pavement is not a function of the mass of the material covering that point (Jordaan, 1994).

3. APPLICABILITY OF METHODS BASED ON LINEAR ELASTIC THEORY

Rehabilitation design methods, which incorporate theoretical mathematical models, are based on sound engineering principals. Because pavement response is measured in basic material concepts of stress and strain, these methods should be applicable for use on all types of materials (including cementitious and new materials). However, as discussed previously, the application of linear elastic theory in road pavement layers only represents an idealisation of natural material behaviour and incorporates various assumptions, which could have an influence on the accuracy of the prediction of the response of some materials under certain conditions. Therefore, rehabilitation design methods incorporating this theory should be tested with regard to material, loading and environmental conditions representative of those where the method will be used. The accuracy of predictions as determined by such practical validations should be used to decide on the adequacy of a specific method for use under specific conditions. Jordaan (1988) discusses this in detail and for more details readers are referred to this reference.

Furthermore, because of the relative complexity of theoretically based methods as compared to empirically derived methods, there is a tendency to simplify theoretically based methods. Invariably this is done by incorporating additional assumptions, which could have a detrimental effect on the general applicability of a specific method. Therefore, a study of pavement rehabilitation design methods should include a detailed investigation of their derivation in order to determine the assumptions made, and thus their limitations (Jordaan 1994).

Research by Monismith et al (1967), Brown and Pell (1967) and Dehlen and Monismith (1970) have shown that linear elastic theory may be used to give an acceptable estimate of expected pavement behaviour. However, various limitations in the practical implementation of the theory have also been pointed out. Most of these limitations are connected to the assumption that the elastic properties of all pavement materials are stress independent (Jordaan, 1994).

It is well known and documented (Grant and Netterberg (1984), Monismith et al, 1967, Maree et al, 1982, Freeme et al, 1982 and de Beer et al, 1997) that temperature and moisture changes could have a significant effect on the behaviour of pavements. The mathematical model on which linear elastic theory is based assumes moisture and temperature to be constant. Therefore, methods incorporating linear elastic theory should provide for the effects of moisture and temperature to be included in behaviour predictions through additional functions. Freeme et al (1982) stated that the effect of environment, i.e. moisture and temperature, are accounted for by including them in the material properties but are, in addition, accounted for in the design of the subgrade. Techniques have also been developed to take actual material behaviour into account in the analysis of pavements, using linear elastic theory (Jordaan, 1994).

Linear elastic theory can only be used to predict pavement response in terms of stress, strain and elastic displacement. The theory cannot be used to predict either permanent deformation or fatigue. Limiting values (criteria) for strain and/or stress as related to distress are usually determined empirically using laboratory or in-situ material tests to establish transfer functions. The calculated stress and strain within the pavement are evaluated against these criteria (transfer functions). These relationships between stress and/or strain and expected pavement life are often subjected to limitations, usually associated with empirical methods such as their applicability to types and conditions of materials, environment and loading (Jordaan, 1994).

4. REHABILITATION AND DESIGN METHODS BASED ON LINEAR ELASTIC THEORY

Most of the theoretically based pavement rehabilitation design methods that have been developed to a stage where practical implementation is possible have been based on linear elastic theory. However, many of these methods have incorporated simplifications such as the use of design curves, design charts or behaviour catalogues. These simplifications are mainly to in-situ characterise pavement materials in terms of their elastic properties (E modulus and Poisson's ratio) (Jordaan, 1994). This has led to the development of various relationships between some measurable pavement properties such as surface deflection, and the in-situ elastic properties of the pavement. Existing procedures range from those which are empirically derived to those based on the theoretical simulation of pavements using linear elastic theory. Therefore, the procedure of material characterisation used by a particular method based on a theoretical approach is likely to have an effect on its general applicability (Jordaan, 1994). The South African Mechanistic Design Method (SAMDM) (Theyse et al, 1996 and Jordaan, 1994), which principals will be used in this analysis, has been developed largely from the results of extensive Heavy Vehicle Simulator (HVS) testing and is based on the non-hereditary linear elastic stress strain theory.

5. NON LINEAR BEHAVIOUR OF PAVEMENT LAYERS

Linear elastic layer analysis models are widely used, efficient, and readily available, but do not account directly for the fact that pavement materials respond non-linearly to applied stresses. To account for the non-linearity of pavement materials, finite element computer models have been developed. These finite element models in general are more complex, require more computer run time and more sophisticated tests must be performed to obtain the material properties for input (Roque et al, 1992).

It is well known and documented (Uzan et al (1992), Horak (1987), Ullidtz et al (1987), Stock and Brown (1980), Horak (1986) and Rohde et al (1992)) that pavement layers and materials are non-linear, non-uniform and stress dependent. The non-linearity and non-uniformity of the subgrade are of particular concern in the analysis of pavement layers and the calculation of the effective elastic moduli of the subgrade from surface deflection basin measurements. Currently, the South African Mechanistic Design Method (SAMDM) does not accommodate the non-linearity of the subgrade (Horak, 1986). The non-linearity of the subgrade is accurately accounted for by the following two methods:

- non-linear backcalculation techniques based on a finite element approach and/or programs (Rohde et al, 1992), and
- non-linear backcalculation procedure by means of the Multi-Depth Deflectometer (MDD) approach (Horak, 1986).

Rohde et al (1992) stated that although the non-linear elastic backcalculation approach based on a finite element model is probably the only available method to fully account for the non-linear elastic behaviour of soils, it is too costly, complex and cumbersome for daily use.

Traditionally subgrade stiffness is usually defined by a semi-infinite layer thickness (linear elastic theory assumption), which made it difficult to account for the non-linear behaviour of the subgrade. Subgrades are usually modelled as a layer containing a constant E-modulus of semi-infinite thickness. In order to simulate pavement response under such conditions the subgrade is represented by an "average" modulus. This modulus will usually be higher than the actual value at the top of the subgrade and lower than actual in depth to achieve balance. The most vulnerable point in the subgrade is at the top of the subgrade, where the E-moduli is normally the lowest (Jordaan, 1994). By introducing a semi-infinite layer of a high modulus (rigid layer) in depth, a more accurate representation of the actual in-situ E-modulus can be simulated (Jordaan, 1994). An improvement or minor deviation to the linear elastic approach is thus to use a rigid layer approach instead of a semi-infinite layer, which accounts for changes in the subgrade stiffness. Rohde et al (1992) showed by using a rigid layer underlying the subgrade, at a determined depth, changes in subgrade stiffness can be accounted for by deflection analysis routines based on the layered elastic approach.

As discussed above the subgrade plays an important role in simulating pavement behaviour. Ullidtz et al (1987) stated that the subgrade usually contributed 60 % to 80 % of the total deflection. It is important to take cognisance of the fact that the subgrade materials of the Northern hemisphere (Ullidtz et al, 1987) and the Southern hemisphere differ in strength and bearing capacity. The subgrade material strengths of the Southern hemisphere provide better support than that of the northern Hemisphere. Ullidtz (1983) also stated that a small error in the determination of the subgrade modulus could lead to large errors in the effective elastic moduli of the other layers. For the same reason, the non-linearity of the subgrade must be considered.

Research by Roque et al (1992) showed that accurate prediction of deflections, stresses and strains can be obtained from non-destructive testing (NDT) devices (i.e. surface deflection measurements) by using linear elastic analysis to predict the non-linear response of pavements. A comprehensive analysis, on 16 different pavement sections, was performed using both linear and non-linear finite element models on a broad range of pavement structures and material properties. The finite element computer program ILLIPAVE was used to predict non-linear response, while the computer program BISAR was used in the elastic layer analyses. Excellent correspondence was observed between surface deflections predicted by linear and non-linear analyses performed at a load level of 40 kN. From the research, the following conclusions were made by Roque et al (1992):

- effective elastic layer moduli can be determined to predict the non-linear response of pavement structures accurately when these E-moduli are used in elastic layer analysis,
- non-linear response of crushed stone base courses may be adequately represented by one effective layer modulus in linear elastic analysis,
- non-linear response of the different subgrade pavement structures investigated may be adequately represented by two elastic layers and corresponding effective layer moduli,
- the upper 300mm of the subgrade should be modelled as a separate layer for backcalculation of effective elastic moduli from NDT deflections, and in subsequent predictions of pavement response using elastic layer analysis, and
- the use of additional elastic layers and corresponding moduli may allow for better prediction on weak pavement structures on silty-sand, but may be impractical owing to difficulties to determine additional moduli reliably from NDT deflections.

6. IDENTIFICATION OF PAVEMENT BEHAVIOUR STATES

Before the material properties (stiffness or E-moduli) of a pavement structure can be determined for use in a mechanistic analysis (based on linear elastic theory), it is important to assess the behaviour and material state of such a pavement. During the "life" / "Functional life" of a pavement structure, the state of the pavement will undergo different phases of deterioration and subsequently the behaviour and/or state of the different layers will change. During reconstruction or rehabilitation of a pavement, the state of the underlying layers will change during the construction phase with subsequent changes in stiffness, stress and strain of the successive pavement layers. By identifying the general behaviour of different material types, an understanding of their likely behaviour can be identified. Because of the wide variety of different layers as well as material variability, the material state will differ for each pavement composition. It is therefore important to simulate the pavement's behaviour accurately in order to model the pavement realistically for rehabilitation design purposes.

6.1 Pavement balance

The behaviour of a pavement can, inter alia, be described in terms of the strength-balance of a pavement (Kleyn, 1984). Jordaan (1994) describes pavement balance as the relative relationship between the load bearing properties of the successive pavement layers.

The concept of balance within the pavement supports the principal of the interaction between the layers and helps to determine whether the pavement structure is likely to change its state rapidly or remain in a stable state in the future. Balance is defined as the state of the pavement in which the layers are not overstressed (Freeme et al, 1987). Pavement structures containing different pavement layers will change in time and different trends in behaviour have been documented during HVS tests done in South Africa (de Beer et al, 1988, Freeme et al, 1982, Freeme et al, 1987, Maree et al, 1982, Jooste et al, 1997). Research recently done by Jooste et al (1997) confirmed that pavement balance, behaviour and state change during HVS testing. This was also demonstrated earlier by Kleyn (1984).

Pavements are constructed (within practical limitations and specified tolerances with all layers fulfilling design criteria. This depends on the required "strength" of a specific layer. Consequently, relatively large differences in the structural strength and bearing capacity between successive layers may exist. In these cases, the strength of the layers may not be balanced and the pavement structure may be classified as being poorly balanced. *In time, under the action of traffic, pavement layers tend to become balanced in terms of the bearing capacity of the pavements*. The classification of the pavement in terms of strength balance gives invaluable information and insight into the expected future behaviour of the pavement. Poorly balanced pavements usually contain layers, which are relatively stronger or weaker in terms of the rest of the pavement. These layers can be identified during field investigations and the potential influence of such layers can be assessed in the mechanistic modelling of the pavement (Jordaan, 1994).

A pavement can become unbalanced due to the ingress of water into particular layers or owing to the changed state of the material through the action of abnormally heavy loading and environmental changes (Freeme et al, 1987). A pavement is balanced when the stiffness of the successive pavement layers are such that there is no excessive build-up of stress between two successive layers and when strains are compatible (Sanders et al, 1993). To achieve balance within a pavement some of the layers may de-densify or de-compact while other layers may compact depending on the external factors (pavement composition, material type, moisture, loading, density, compaction, stress differences etc.), which will play a role. The effective elastic moduli may also show some change as a result of an adjustment in the balance of the pavement. Research by Heukelom and Klomp (1962) showed that the stability between two successive layers can be achieved when the E-moduli ratio (stiffness) is between approximately 0.5 and 2.2 (depending on the vertical stress). The effect of modular ratios where compaction and de-compaction may occur according to Heukelom and Klomp (1962, 1967) can be seen in Figure 1. The effect that modular ratio has on the balance between layers and its indirect effect or influence on the stiffness and stresses in pavement layers warrants further research.

The effective E modulus of granular layers is a function of the modulus of the supportive layer and the granular interlocking achieved during the construction of the layer (Seed et al, 1967). Tensile stresses occur in granular layers when the relationship E granular / E subgrade > about 1. Figure 1 shows a plot of the relationship between the tensile stress (σ_r) at the bottom of a granular base layer in a three layer pavement, and the applied vertical surface stress (σ_o). It is seen that the bottom of the layer is in tension when E2/E3 > about 1. Compression would normally result in the compaction of materials, while tension would result in the expansion or de-compaction of materials. However, due to friction between grains, the granular layer can withstand a certain amount of tension without expanding. The friction stress resisting radial displacement is defined as (Seed et al, 1967):

$\sigma_f = g\ \sigma_r$

Where:

σ_f = frictional stress
g = aggregate interlocking factor ($0 < g < 1$)

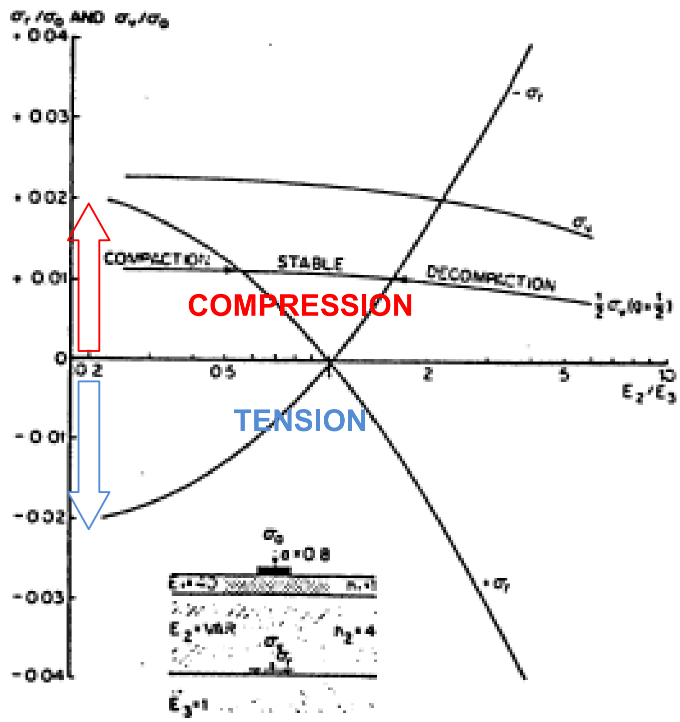

Figure 1: Approximation of stability limits for granular bases (after Heukelom and Klomp, 1962) , (after Monismith et al. , 1967)

Also shown in Figure 1, when g = 0,5 the ratio E2/E3 ≈ 2. The effect is further demonstrated to show modular ratios where compaction and de-compaction may occur. The mass of the material above the point of tension will contribute to the confining effect and increase interparticle friction, resulting in moduli ratios of up to 3 to 5. The effect and occurrence in granular layers of tensile stresses could be quantified more accurately if a gradual reduction in modulus, due to the stress dependent nature of the material, is taken into account.

Taking all the above into consideration, one would asked what has this to do with stimulating the non-linearity behaviour of the different pavement layers. The answer to this is the fact that for granular materials it is natural for the different pavement material layers to compact or to de-densify or de-compact once certain stress relationships have been achieved and thus in theory and in practice one would find that you hardly seldom get granular layers with a E2/E3 > 2 in the field. Once a relationship has started to develop where E2/E3 > 2, the layer will start to decompact and/or compact in order to achieve a balance. The only place in the field where one would find E2/E3 > 2 is when for e.g. the subbase and/or other layers are strongly stabilised and still intact. Thus when the layer act in tension and it still can "tolerate" such a relationship. Once the stabilised layer starts to break down, this whole process where stiffness and subsequently stresses or strains are exchange in order to achieve a balance in the pavements starts over again. When a road is due for rehabilitation (normally after 20 to 30 years), in general, most of the stabilised layers are already in an equivalent granular layer phase and the effect of the stabilised layer is not so pronounce as when initially stabilised. It is very important to take cognisance of this when the pavement layers are modelled and when E-moduli need to be calculated or determined. Various test methods can assist the practitioner to determine if the stabilised layer is strongly stabilised etc. and ultimately help with the back calculation criteria to be used for various pavement layers.

7. DETERMINATION OF EFFECTIVE ELASTIC MODULI FROM SURFACE DEFLECTION MEASUREMENTS

7.1 General

In the past only maximum deflection and radius of curvature were calculated with Road Surface Deflectometer (RSD) data. Recently, better use was made of the full deflection basin for calculating other deflection basin parameters. In order to make use of the measured deflection basins more effectively, various researchers have used the full deflection basin to calculate effective elastic moduli (Horak, 1988).

Procedures have been developed to calculate elastic moduli from surface deflection measurements. In such a procedure, it is practice that at least the same number of deflections should be used as the number of layers in the pavement structure. For the purpose of this paper the CHEV15 programme (Coetzee et al, 1982) was used to *accurately calculate* up to 15 layer's moduli. In Figure 2, it is illustrated how the measured deflections, from the surface deflection basin are used in a typical four layered elastic system. It is assumed that the load is distributed through the pavement system by a truncated cone intersecting the pavement layers at an angle (α). The angle (α) can vary between 30° and 60°. Research by Horak (1988) showed that the E-moduli determined at a 30° truncated cone were found to provide effective elastic moduli that were better related to those determined with the MDD measurements. However, this is a function of pavement and material types. Based on the concept of linear elasticity, deflection δ_4 at a distance r_4 is due to the elastic compression of layer 4 while deflection δ_3 at distance r_3 is due to the elastic compression at layer 3 and 4. The result is that maximum deflection δ_1 in Figure 2, is due to the deflection of the effective elastic moduli of all layers (δ_1 = f(E1, E2, E3, E4)) (Horak, 1988).

The fact that it is possible to measure / determine much more deflection measurements on your deflection bowl and that currently there are more and more software programmes that is available (for e.g. the General Analysis for Multilayered Elastic Systems (GAMES) (MePADS, CSIR 2006) and CHEV15 (Coetzee et al, 1982)), to accurately calculate up to 15 layer moduli, it is made easier today to effectively simulate the non-linear behaviour of pavement layers. Although it will be discuss in more detail later, at this stage it is important to take cognisance from the fact that four or five layer programmes used to determine the effective elastic moduli is "old technology" / vintage. Engineers need to take the bold step in using software programmes such as GAMES (MePADS, CSIR 2006) and/or CHEV15 (Coetzee et al, 1982) etc. in order to simulate pavement models more accurately by using more pavement layers in the analysis during the back-calculation process. By doing this, not only will they achieve to better simulate the non-linearity of the pavement layers, but they will also get better prediction of structural or "functional" pavement life from these calculations.

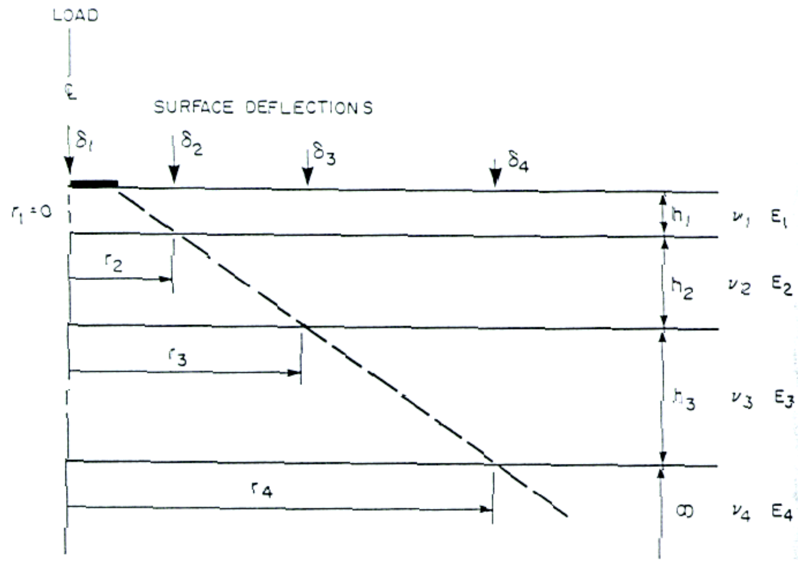

Figure 2: Four layer elastic representation of a pavement system (FHWA, 1984) (after Horak, 1988)

7.2 Backcalculation of effective elastic moduli

The backcalculation process can be described as the characterisation of material properties in an iterative process using a theoretical model, pavement thickness, Poisson's ratio and estimated moduli, to produce theoretical deflections that match field deflections within a specific tolerance. Complete surface deflection basins are used in backcalculation procedures. The end result of the backcalculation process is an effective elastic modulus value for each pavement layer, which will be used as input to directly calculate the distress determinants. Typical deformation and fatigue relationships / curves were developed through HVS tests between 1972 and 1982 as input in the mechanistic design procedure (Freeme et al, 1982).

Although various computer programs and automatic simulations (backcalculations) of pavement layer E-moduli are available, manual backcalculation procedures can also be used. Research by Lacante et al (1991) showed that automatically derived pavement layer E-moduli can be problematic resulting in gross inaccuracies in the analysis of pavements. However, with new programmes and technology available and with experience, these inaccuracies can be minimised or eliminated. Manual backcalculation basically involves a trial and error procedure using one of the elastic layered programs to match a set of measured surface deflections or deflection bowl parameters. An initial set of moduli is assumed and surface deflections are calculated using the program and compared with measured deflections. Moduli are adjusted based on the comparison and the procedure is repeated until accepted match between measured and calculated deflection basins is achieved (de Beer et al, 1997).

Horak (1988) suggested the following backcalculation procedure for a typical four-layered pavement:

- In the backcalculation procedure the effective elastic modulus of the subgrade (E4) is calculated first by fitting the deflection at distance r_4 to the measured deflection δ_4 (see Figure 2),
- The next step is to calculate E3 by calculating and fitting the deflection at distance r_3,
- Effective elastic moduli are therefore calculated from the lower layers upwards by fitting the deflections radially inwards towards maximum deflection.

According to Rohde (de Beer et al, 1997) the following key issues regarding backcalculation of layer moduli should be kept in mind during the process:

- Backcalculation requires expertise and engineering judgement. Pavements tested are considerably more complicated than the relatively simple multi-layered elastic model being used to explain the measured deflections. It cannot be expected that the multi-layered elastic model will be able to explain/model all tested pavement sections automatically,
- The majority of backcalculation programs currently use available multi-layered elastic theory to derive a model to explain the measured deflections. Backcalculated layer moduli should be viewed as “model properties” and not “material properties”. They are model dependent and do not correlate well with laboratory moduli which were determined under different stress, moisture and load conditions,
- Backcalculated moduli should be realistic. This is essential because more than one combination of layer moduli can lead to the same deflection,
- The number of layers (n) in a model should be less than the number of deflections (nd) being matched in the deflection analysis (nd=n+1),
- The E-moduli determined through backcalculation are only applicable to the moisture, temperature and stress condition at the time of testing. Moduli should be adjusted during reference conditions,
- Do not average two or more deflections prior to backcalculation. Backcalculate first and then determine statistical parameters of the backcalculated moduli,
- Deflection analyses are very sensitive to layer thicknesses. Determine the actual thicknesses as reliably as possible. DCP test results are very useful,
- On sections with shallow bedrock or sandy subgrades a model with an infinitely thick subgrade will lead to totally unrealistic moduli,
- Moisture saturated layers in the undrained condition also lead to unrealistic high moduli derived from impulse testing, and
- Moduli of pavement layer material (unbound) may also be load frequency dependent.

7.3 Pavement modelling and non-linear behaviour of subgrade

Research done by Jordaan (1994) “The South African Mechanistic Pavement Rehabilitation Design Method, Appendix B - Modelling of the effective elastic properties of pavement layers”, provides the Engineer with practical guidelines on the modelling of the effective elastic moduli for different pavement materials. The criteria in Appendix B in this particular report is very important and the engineering practitioner is encourage to study these criteria since the guidelines given in this report are very helpful to understand how to properly model your pavement models and in determining and/or simulating the effective elastic moduli during the back calculation process. Herewith an example of some guidelines as extracted from Jordaan (1994): "Experience in South Africa has shown that a bituminous treated layer should seldom (depending on the temperature (MMPT)) be modelled for predicting the of in-situ pavement behaviour during rehabilitation investigations, using an effective elastic modulus of more than 1500 MPa (Freeme and de Beer, 1983). Depending on the temperature and the mix characteristics, the E modulus can be much lower, as shown in the Shell figure "Characteristic relationships between mix stiffness and mix temperature" (Shell, 1978)". Also seen in this Shell figure (Jordaan, 1994) is that, "……depending on the mix characteristics, the E modulus of an asphalt layer at 20°C could vary between about 1000 MPa and 6000 MPa. Similarly, at 40°C, the E modulus of the asphalt layer could vary between about 150 MPa and 700 MPa". From Shell's research it is clear that at the operating road temperature when the deflections are measured (normally higher than 40°C), the effective elastic moduli is not expected to be higher than at least 700 - 1000 MPa. Taking this, as well as the above Freeme and de Beer's (1983) recommendations into consideration, the following questions may be asked – "What E-moduli are used in the industry to determine or calculate the asphaltic base's effective elastic moduli for a pavement that is more than 20 years old and cracked?" and "How will this then influence modelling the rest of the E-moduli of the other layers ?" etc.

One important aspect that needs consideration in the modelling of a pavement structure is the non-linearity of the subgrade. *Ullidtz (1983) stated that a small error in the determination of the subgrade modulus could lead to large errors in the effective elastic moduli of the other layers.*

Traditionally, subgrades are usually modelled as a layer containing a constant or "average" E-modulus of semi-infinite thickness, which made it difficult to account for the non-linear behaviour of the subgrade. This modulus will usually be higher than the actual value at the top of the subgrade and lower than actual in depth to achieve balance. Jordaan (1994) stated that the most vulnerable point in the subgrade is at the point of lowest modulus, i.e. at the top of the subgrade. By introducing a semi-infinite layer of a high effective elastic modulus (rigid layer) in depth, a more accurate representation of the actual in-situ E-modulus can be simulated (Jordaan, 1994). An adjustment or minor deviation to the linear elastic approach is thus to use a rigid layer approach instead of a semi-infinite layer, which accounts for changes in the subgrade stiffness. However, there are a number of Engineers still today that are using the semi-infinite subgrade layer approach with subsequently less accurate output from these models. Rohde et al (1992) showed that by using a rigid layer underlying the subgrade, at a determined depth, changes in subgrade stiffness can be accounted for by deflection analysis routines based on the layered elastic approach.

Research by Roque et al (1992) showed that accurate prediction of deflections, stresses and strains can be obtained from Non-Destructive Testing (NDT) devices (i.e. surface deflection measurements) by using linear elastic analysis to predict the non-linear response of pavements. Thus, pavement structures can be analysed by using "non-linear" elastic material characterisation through an elastic layer procedure. He suggested that at least the upper 300mm of the subgrade should be modelled as a separate layer for back-calculation of effective elastic moduli from NDT deflections, as well as in subsequent predictions of pavement response using elastic layer analysis. He also stated that a better prediction of the effective elastic moduli may be found if additional elastic layers and corresponding moduli be used. Taking this into consideration, it can be concluded that the more pavement layers used to model the pavement structure the more accurately the model will represent the non-linearity of the pavement structure and layers.

The above findings from Roque et al (1992) and other researchers confirmed that a better representation of the non-linear characterisation of the different pavement layers can be achieved by modelling more than the traditional four to five layers (which may include a semi-infinite layer) and by introducing additional pavement layers in the subgrade when simulating the non-linearity of the subgrade (for e.g. using a total of eight layers).

For the purpose of this paper the following two pavement structures (A and B) were modelled using CHEV 15 and by using the same deflection basin measurements etc. but with different number of pavement layers etc.:

- Model A : In the first model / analysis, the same pavement structure and deflection measurements were used to determine the effective elastic moduli by using five layers of which the last layer is a semi-infinite layer (see Figure 3 below),
- Model B : The second pavement structure was modelled by using additional pavement layers to simulate the upper 150mm of the subgrade (as a separate layer) and by placing a semi-infinite layer of a high effective elastic modulus (rigid layer) at a depth of 1.5m. In order to minimise the error due to the correct placement or determined depth of the rigid layer, the subgrade was further subdivided into two additional layers. The effect of the subgrade depth and thickness (semi-infinite) is then almost negligible and it accounts for the non-linear behaviour of the subgrade. Thus an eight layer modelled have been developed and effective elastic moduli calculated.

The different pavement models together with their effective moduli are given in Figure 3 below.

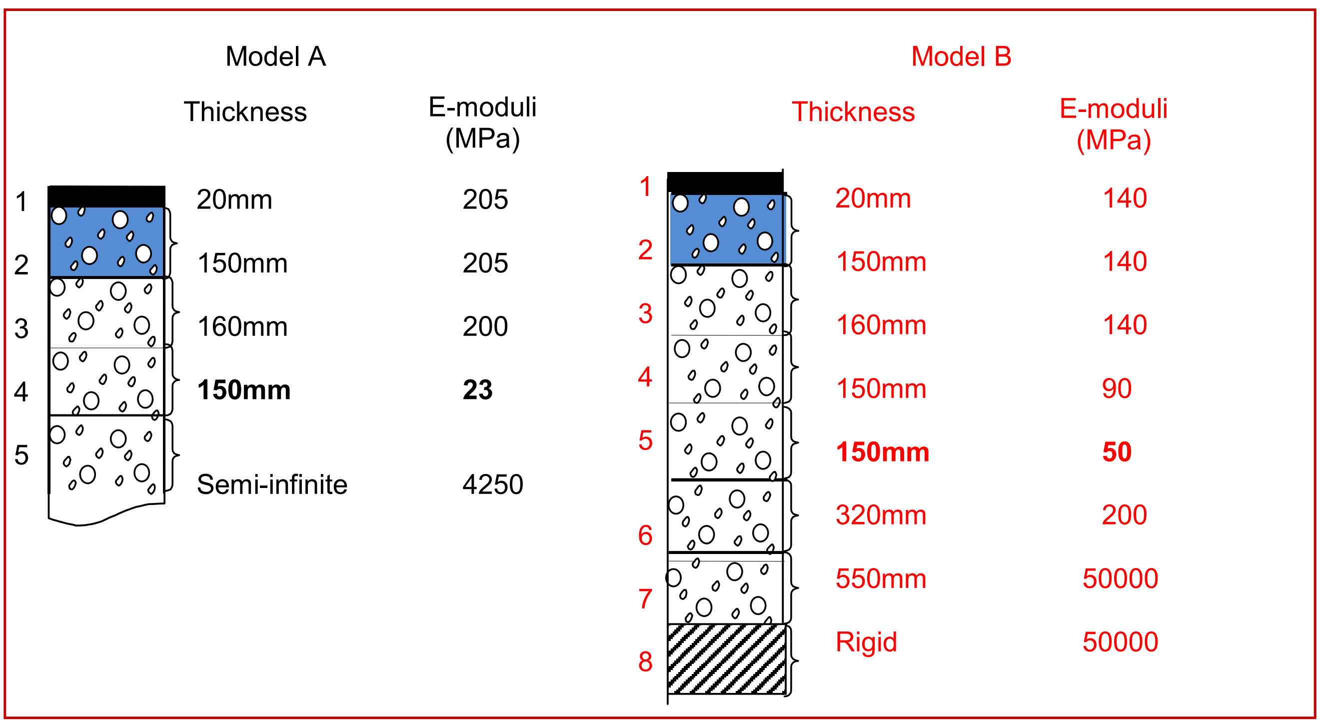

Figure 3: Pavement models A and B with their associated effective elastic moduli

Comparing the E-moduli ratio simulated in Model A with research done by Heukelom and Klomp (1962, 1967) etc., it is difficult to see how a pavement that is almost 30 years old and is supposed to be in balance and having such a high E3/E4 ratio (200/23). Comparing the subgrade E-moduli simulated in Models A and B, there is a major difference in the result of the subgrade E-moduli (23 vs. 50).

In Model B by simulating the top 150 mm of the subgrade separately and by subdividing the subgrade into additional pavement layers, Roque et al's (1992) research has been confirmed and validated. Thus, by using a linear elastic analysis it is possible to predict the non-linear response of pavements and characterise the non-linearity through an elastic layer procedure. A better prediction of the effective elastic moduli has also been found with the addition of additional elastic layers and corresponding moduli and a more balance pavement has been modelled (which is expected from a 30 year old pavement). The top of the subgrade (point of lowest modulus), which according to Jordaan (1994) is the most vulnerable point in the subgrade has also been modelled more accurately by introducing a semi-infinite layer of a high effective elastic modulus (rigid layer) in depth, simulating the upper 150 mm subgrade layer separately and by the addition of additional subgrade pavement layers. It is interesting that note the position or difference in the subgrade depth by comparing the two models or approaches. Hence the question can be asked, "When modelling a pavement structure with 5 layers, do you get an accurate characterisation and the correct position or depth of the most vulnerable pavement layer in your pavement structure (i.e. the subgrade)?"

8. SUMMARY AND CONCLUSION

The following summary and conclusions can be made:

- The current practice or tradition by using five pavement layers when modelling a pavement structure produces a pavement model with E-moduli that does not necessarily represent a pavement structure that is balanced and hence the stresses and strains within such a model may not necessarily be accurate for calculating the "functional pavement life" of the pavement layers. Such a pavement model, especially a pavement structure that is more than 30 years old with the effect of stabilised subbase layers almost negligible, make it very difficult to explain or to validate the E-moduli or stress ratio relationship between the different pavement layers as explain by research done by Heukelom and Klomp (1962, 1967).
- By using such a five layer model approach, it is difficult to accurately simulate or calculate the most vulnerable point of the pavement which is at the top of the subgrade and subsequently the correct position or depth thereof.
- One important aspect that needs consideration in the modelling of a pavement structure is the non-linearity of the subgrade. *Ullidtz (1983) stated that a small error in the determination of the subgrade modulus could lead to large errors in the effective elastic moduli of the other layers.* The moduli calculated in Model B compare to the E-moduli calculated in Model A clearly demonstrate the "large error" that can occur in the determination of the effective elastic moduli as predicted by the research done by Ullidtz (1983).

- Software programmes such as GAMES (MePADS, CSIR 2006) and/or CHEV15 (Coetzee et al, 1982) etc. are available to simulate pavement models more accurately by using more pavement layers in the analysis during the back-calculation process. By doing this, the non-linearity of the pavement layers are better modelled which then leads to a better prediction of structural or “functional” pavement life.
- The non-linear response of the subgrade as presented in this paper in Model B has been adequately modelled by the subdivision of the subgrade layer into additional layers. The top of the subgrade (150 mm), normally the most vulnerable point in the subgrade where the lowest moduli occur, together with its correct depth were successfully simulated and modelled and a more balance pavement structure was modelled by using more than the traditional 5 layer model approach (i.e. eight layers). This also confirmed and validates the research recommendations as proposed by Roque et al**’s** (1992) which inter alias include :
    - effective elastic layer moduli can be determined to predict the non-linear response of pavement structures accurately when these E-moduli are used in elastic layer analysis,
    - non-linear response of the different subgrade pavement structures investigated may be adequately represented by using more than two elastic layers and corresponding effective layer moduli,
    - the upper 150mm - 300mm of the subgrade should be modelled as a separate layer for backcalculation of effective elastic moduli from NDT deflections, and in subsequent predictions of pavement response using elastic layer analysis.

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