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Benchmarking the structural condition of flexible pavements with deflection bowl parameters

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The falling weight deflectometer (FWD) is used worldwide as an established, valuable, non-destructive road testing device for pavement structural analyses. The FWD is used mostly for rehabilitation project level design investigations and for pavement management system (PMS) monitoring on a network basis. In project level investigations, design charts based on both empirical relations and mechanistic or theoretically based approaches are often used to provide structural evaluations and rehabilitation options. The full mechanistic approach normally uses multi-layer linear elastic theory and back-calculation procedures that have come under scrutiny owing to the inaccuracy of results. A semi-mechanistic, semi-empirical analysis technique has been developed in South Africa in terms of which deflection bowl parameters, measured with the FWD, are used in a relative benchmarking methodology in conjunction with standardised visual survey methodology to give guidance on individual layer strengths and pinpoint rehabilitation needs. This benchmark methodology enables the determination of the relative structural condition of the pavement over length and in depth without the requirement for detailed as-built data. A further correlation study with calculated surface moduli and deflection bowl parameters is presented here for granular base pavements, which can enhance benchmarking methodology.

INTRODUCTION

The South African pavement design procedure is a mechanistic empirical (ME) procedure that utilises basic engineering properties such as the layer elastic modulus, Poisson's ratio, layer thicknesses and loading conditions (Jordaan 1988, 1990) as input variables. Assumptions are made regarding the material-related Poisson's ratios, whereas the layer thicknesses must be determined accurately and elastic moduli can be derived from known ranges of values for specific material types and their behaviour states (Freeme 1983). Material characterisation can also be derived from field and laboratory tests. Measured deflection bowls can be used to undertake back-calculations with linear elastic software to derive the elastic modulus (E-value) of each layer. In essence, the measured deflection bowl is used as reference by changing the E-values of the various pavement layers until the theoretically calculated deflection bowl fits the measured deflection bowl within pre-determined tolerances. The iteration process is started by fixing the E-value of the subgrade that correlates with the outer region of the deflection bowl. Thereafter the layer on top of the subgrade is fixed to fit the deflection bowl of the region closer to the point of loading. By fixing the E-values of the structural layers progressively from the subgrade to the base

layer, the deflection bowl is compared with the regions progressively closer to the point of loading (Horak 1988).

Standard software such as ELSDEF, IDME, PADAL, MODULUS and ISSEM4 are some of the back-calculating programs developed in the late 1980s and early 1990s that utilised this technique (Horak 1988; Lacante 1992). The pavement layer material type composition and layer thickness relationships of the pavement must be known accurately in order to do a mechanistic analysis of the pavement. Typical pavements in South Africa consist of a rather stiff subgrade, and stabilised layers are often used as sub-base. The base layers may often be cementitious, but are mostly granular and vary in quality from high-quality, freshly crushed rock to natural gravel. Since an in-depth knowledge of pavement materials and their behaviour is needed to perform back-analyses, it is an area of specialist expertise. Worldwide development of back-analysis procedures and associated software took place in the past ten years, but have run into various problems of credibility owing to the uncertainties regarding material characterisation, the uniqueness of measuring equipment, personal interpretations and basic material variabilities (Ullidtz 2005).

A semi-mechanistic empirical analysis procedure developed in South Africa utilises

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Figure 1 Curvature zones of a deflection bowl

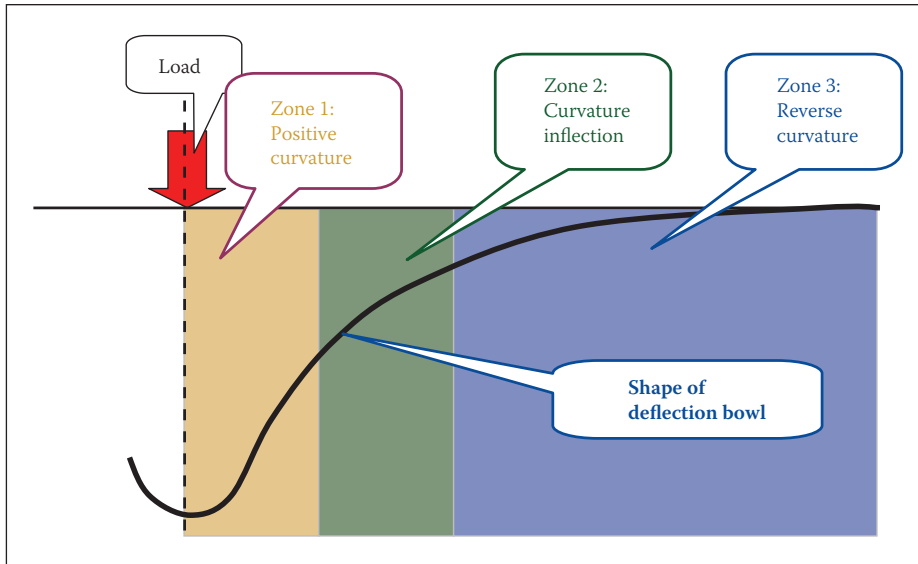


Table 1 Summary of deflection bowl parameters

Parameter	Formula	Zone correlated to (see figure 1)
Maximum deflection	D_0 as measured at point of loading	1, 2 and 3
Radius of curvature (RoC)	$RoC = \left(\frac{(L)^2}{2D_0(1 - D_{200}/D_0)} \right)$ Where $L = 127$ mm in the original Dehlen (1961) curvature meter and 200 mm for the FWD	1
Base layer index (BLI) (previously referred to as surface curvature index, SCI)	$BLI = D_0 - D_{300}$	1
Middle layer index (MLI) (previously referred to as base curvature index, BCI)	$MLI = D_{300} - D_{600}$	2
Lower layer index (LLI) (previously referred to as base damage index, BDI)	$LLI = D_{600} - D_{900}$	3

the measured deflection bowl and its correlations with the structural layers or zones of the pavement structure (Maree & Jooste 1999). Aspects of this approach have been included in the standard rehabilitation design procedure for flexible pavements, namely the Technical Recommendations for Highways 12 (TRH 12) (CSRA 1997) and subsequent improvements to the procedure. Elastic moduli were back-calculated and surface moduli calculated from a data set of measured deflection bowls also used in an original correlation study (Maree & Bellekens 1991). The two derived pavement structural values were then correlated with these deflection bowl parameters describing zones on the deflection bowl. The results of this correlation study confirmed the soundness of the basis of the benchmarking procedure (Maree & Jooste 1999).

In essence deflection bowl parameters can be used in a benchmarking procedure (Horak & Emery 2006) to help identify

weaker areas in the pavement over the length and in the depth of the structure to optimise further detailed investigations. The basis for the benchmarking approach is described, demonstrated and enhanced by using surface moduli calculations (Horak 2006) and further derivatives. Since these benchmark analyses are based on simple spreadsheet calculations using the measured falling weight deflectometer (FWD) deflection bowls, complicated back-analyses using complicated linear elastic layered software or finite element method analyses are not required.

ZONES OF THE DEFLECTION BOWL

When a flexible pavement deflects under the load of a heavy vehicle, the influence of the load will usually extend over an area 1 m to 2 m away from the point of loading, in three dimensions. This deflected area tends to form a circular, deflected indentation known as a deflection bowl. The size and

shape of deflection bowls vary and depend on a number of factors, including pavement composition and structural strength, size of the load contact area, load magnitude, duration of loading, the measuring device used, and temperature (Horak 1987, 1988; Lacante 1992).

Figure 1 shows that a deflection bowl measured under a loaded wheel can be described in terms of three distinct zones. In zone 1, closest to the point of loading, the deflection bowl has a positive curvature. This zone will normally lie within a radius of not more than 300 mm from the point of loading. Zone 2 is the zone where the deflection bowl switches from a positive curvature to a reverse curvature and is often referred to as the inflection zone. The exact position of the point of inflection in zone 2 depends on specific pavement layer structural composition factors. Zone 2 normally lies from about 300 mm to about 600 mm from the point of loading. Zone 3 lies furthest away from the point of loading, where the deflection bowl has switched to a reverse curvature and extends to the normal road surface, in other words, where deflection reverts to zero. Zone 3 normally stretches from about 600 mm to 2 000 mm from the point of loading although its extent will depend on the actual depth of the pavement structure and on the structural response of the subgrade layer.

These three zones of the deflection bowl have distinct associations with various zones of the layers of the pavement structure, which will be explained in more detail later.

DEFLECTION BOWL PARAMETERS

The FWD became the deflection measuring tool of choice in the mid to late 1980s in the United States (Coetzee *et al* 1989; Horak 1988) and South Africa followed suit. The FWD can simulate a moving wheel load and measure elastic response within the entire deflection bowl up to a distance of 1,8 m to 2 m away from the centre point of loading. In South Africa the position of the geophones has been standardised to measure at 0 mm, 200 mm, 300 mm, 450 mm, 600 mm, 900 mm, 1 200 mm, 1 500 mm and 1 800 mm from the centre of the load. This distribution was found to give a fair description of the entire deflection bowl. This measurement of the deflection bowl by means of the FWD led to the definition of various deflection bowl parameters that describe various aspects of the measured deflection bowl.

In table 1 a selected number of deflection bowl parameters and their formulae are summarised as linked to the deflection bowl zones and their formulae based on the measured deflection bowls. The radius of

Table 2 Behaviour states for granular base pavements (CSRA 1997)

Behaviour state	Traffic range (E80s) ('000 000)	Maximum deflection (mm)	BLI (mm)	MLI (mm)	LLI (mm)
Very stiff	12 to 50	<0,3	<0,08	<0,05	<0,04
Stiff	3 to 8	0,3 to 0,5	0,08 to 0,25	0,05 to 0,15	0,04 to 0,08
Flexible	0,8 to 3	0,5 to 0,75	0,25 to 0,50	0,15 to 0,20	0,08 to 0,10
Very flexible	< 0,8	>0,75	>0,5	>0,20	>0,10

Table 3 Deflection bowl parameter structural condition rating criteria for various pavement types

	Structural condition rating	Deflection bowl parameters				
		D_0 (µm)	RoC (m)	BLI (µm)	MLI (µm)	LLI (µm)
Granular base	Sound	<500	>100	<200	<100	<50
	Warning	500-750	50-100	200-400	100-200	50-100
	Severe	>750	<50	>400	>200	>100
Cementitious base	Sound	<200	>150	<100	<50	<40
	Warning	200-400	80-150	100-300	50-100	40-80
	Severe	>400	<80	>300	>100	>80
Bituminous base	Sound	<400	>250	<200	<100	<50
	Warning	400-600	100-250	200-400	100-150	50-80
	Severe	>600	<100	>400	>150	>80

Note: These criteria can be adjusted to improve sensitivity of benchmarking.

curvature (RoC) and the base layer index (BLI) have been found to correlate well with zone 1 (mostly surface and base layers), the middle layer index (MLI) correlates with zone 2 (mostly sub-base layer), and the lower layer index (LLI) correlates with zone 3 (mostly selected and subgrade layers), as illustrated in figure 1. In table 1 the original names of some of these deflection bowl parameters are also indicated, but their names tended to be misleading in terms of the zones and structural zones described above and therefore the more descriptive names BLI, MLI and LLI were used. Owing to the closeness (200 mm) of the geophone to the edge of the loading plate and the associated surface disturbances observed, the RoC is used with less confidence and BLI is used with more confidence to describe zone 1. These variabilities have also been observed in other methods of analysis that tended to rely on the deflection value at 200 mm, such as the Australian method where a curvature ratio is calculated based on that value (Horak & Emery 2006).

EXISTING DEFLECTION BOWL PARAMETER CORRELATIONS

The BLI, MLI and LLI have been found to correlate well with the relevant pavement

structural condition and with zones 1, 2 and 3 respectively of pavement layers of flexible pavements in South Africa (Horak 1988). The use of these deflection bowl parameters in the evaluation of the structural capacity of a pavement were developed and used by several researchers to aid the structural evaluation of South African flexible pavement structures (Maree & Bellekens 1991; Rohde & Van Wijk 1996; Maree & Jooste 1999). Basic correlations and tolerances for these deflection bowl parameters are included in TRH 12 (CSRA 1997) that deals with the rehabilitation design and analysis methodology of flexible pavements.

Maree and Bellekens (1991) and Maree and Jooste (1999) analysed a set of deflection bowls as measured with the FWD at a load of 40 kN or contact pressure of 565,9 kPa for a selection of representative typical South African pavement structures (granular, bituminous and cemented base pavements). High-density FWD surveys were done at intervals of 5 m to 10 m in the outer and inner wheel tracks of the slow, fast and shoulder lanes of these roads. Elastic moduli were determined by means of back-analysis procedures utilising the known layer thicknesses. The pavement structures were analysed mechanistically, their remaining lives determined and correlated with measured

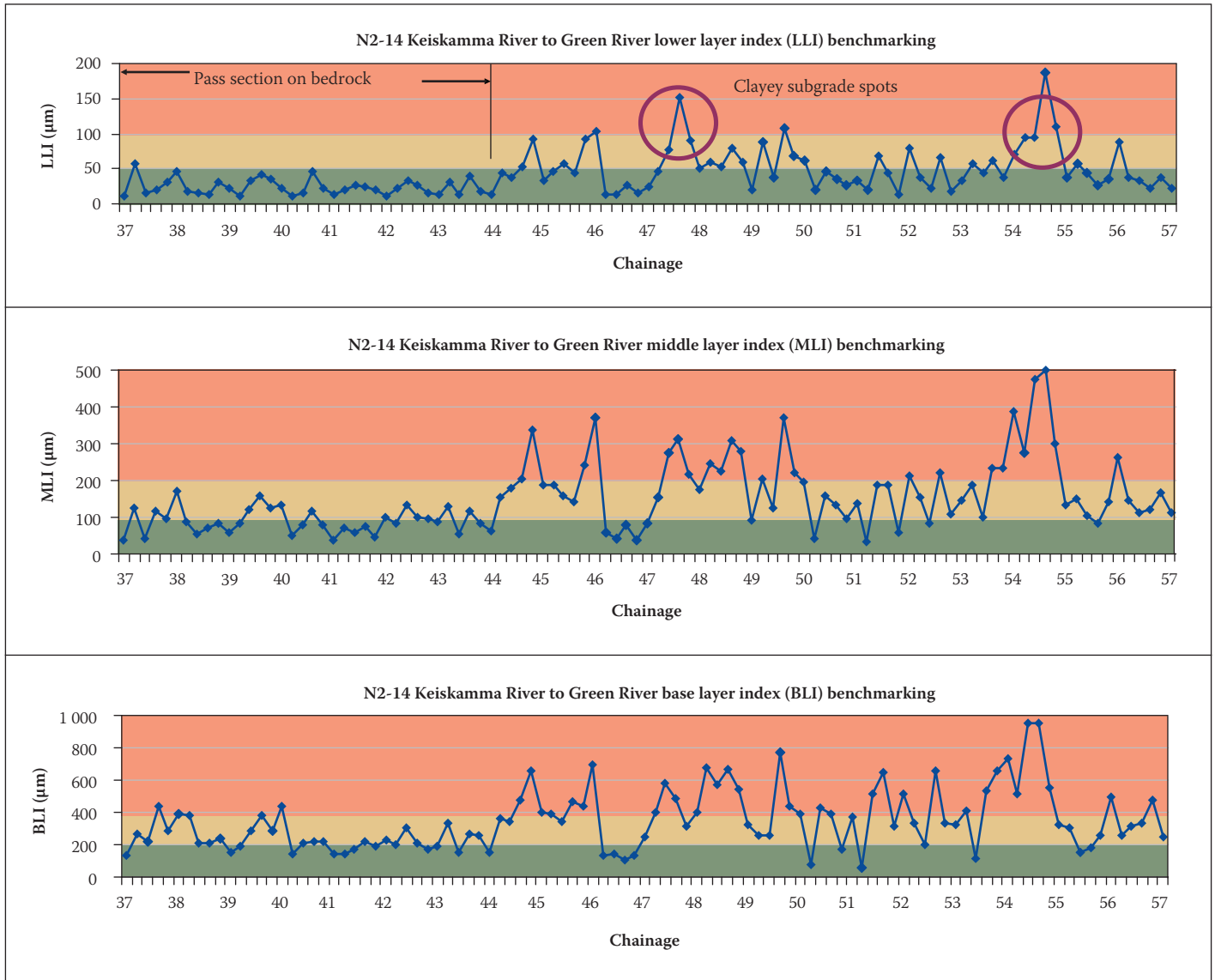
deflection bowl parameters. Correlations were developed for the deflection bowl parameters (BLI, MLI and LLI) and remaining life (expressed in terms of standard or equivalent 80 kN axle repetitions (E80s)) was determined. These correlations were developed for various pavement types (granular, cemented and asphalt bases) and are quite useful in pavement response analysis (Maree & Jooste 1999; Horak & Emery 2006).

However, using these correlations to determine remaining lives as a structural analysis in rehabilitation design and analysis of flexible pavements can lead to oversimplification of a complex structural response and to embarrassing inaccuracies. A more basic or fundamental level of application is advocated by steering away from remaining life calculations and rather using these correlations to enhance the condition and behaviour state of pavement layers (Horak & Emery 2006). It is in effect a benchmarking approach that has its origins in the behaviour state of the pavement structure. The concept of behaviour states of pavements, described by Freeme (1983), originally made use of maximum deflection to classify pavement structural conditions in terms of elastic response. This behaviour state classification was subsequently expanded by Horak (1988) to include the other deflection bowl parameters, which improved the representation of the entire deflection bowl. In table 2 such an example of behaviour state classification for granular pavements is shown, as included in TRH 12 (CSRA 1997). Ranges of deflection bowl parameters and remaining life, as developed by Maree and Bellekens (1991) and Maree and Jooste (1999), are also shown. This classification of basic classes or behaviour states has already proved to be useful in a benchmarking approach.

BENCHMARKING USING DEFLECTION BOWL PARAMETERS

Experience with condition rating of flexible pavements in South Africa has shown that visual condition rating can be linked with such behaviour states and help explain or direct cause of distress diagnosis on a preliminary investigation level. TRH 12 (CSRA 1997) makes extensive use of a structured survey methodology of the visual condition rating of flexible pavements as described in TMH 9 (CSRA 1992). The visual survey results are normally summarised in a simple, three-tiered condition rating description. Visual condition survey ratings allow the pavement to be summarised and presented graphically over the length of the pavement with the three-tiered colour coding condition rating expressed as **sound**, **warning**

Figure 2 Deflection bowl parameter benchmarking of N2-14 (40 kN)



or **severe**. The use of colour provides a simple yet effective graphical summary over the length of a pavement, which enables relative benchmarking of the conditions of sections of pavement sections and helps steer further, detailed investigations.

It is possible to select a similar three-tiered relative structural condition rating for the zone-linked deflection bowl parameters described in table 1. No information on for example pavement layer thickness is needed for such a relative benchmarking since the correlations developed by Maree and Bellekens (1991) and Maree and Jooste (1999) and the behaviour states described in table 2 are used as a basis for the development of such a relative structural benchmarking.

Table 3 illustrates such a benchmarking classification for various pavement types developed for road pavements. In essence it means that the four-tiered classification of behaviour states in table 2 is converted to a three-tiered system by omitting very stiff pavements since they would normally be structurally sound and not of primary

concern in a rehabilitation analysis. The colour coding and rating system normally used in graphical plots is also indicated, namely **sound**, **warning** or **severe**.

By using the same rating system the relative structural strength contribution of zones of layers in the pavement structure can thus be linked to the visual condition rating. Relative or benchmarked structural deficiencies of the related structural layers in the pavement structure can be identified over the length of road. In this fashion the possible cause of structural deficiencies can be deduced from similarly rated and colour coded visual condition surveys. A diagnostic cause and effect of observed visual conditions can therefore be established at an early stage of the investigation and with limited complicated analysis.

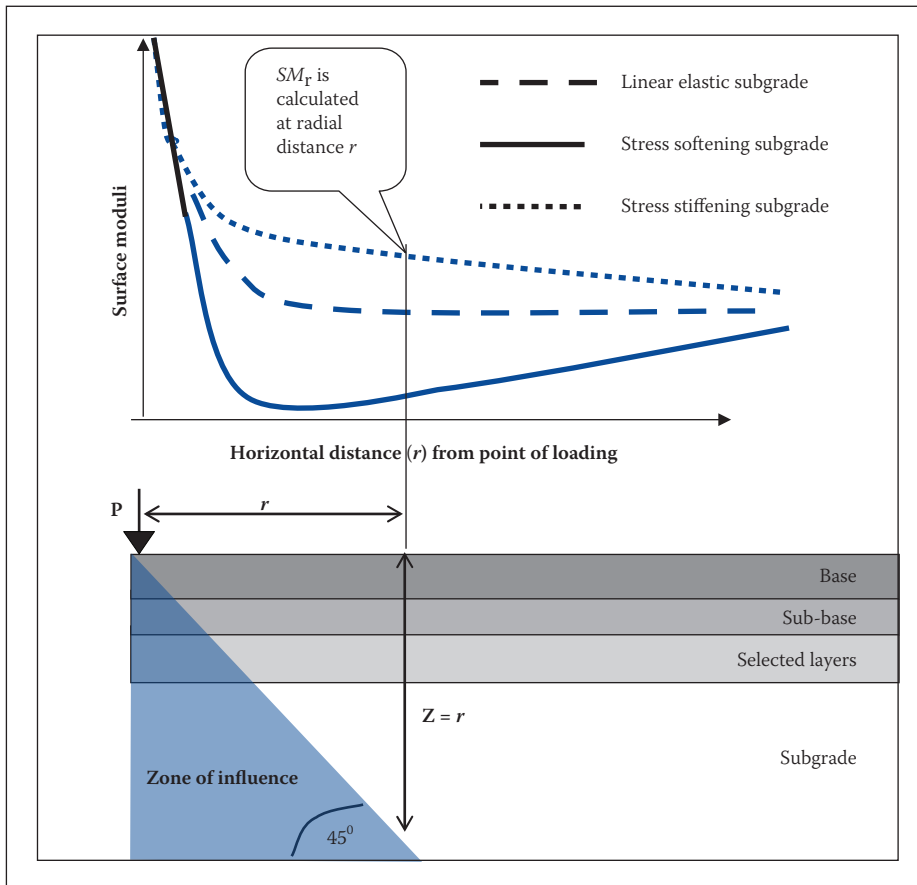
DEMONSTRATION OF BENCHMARKING METHODOLOGY

In figure 2 the application of this benchmarking process is demonstrated based on

LLI, MLI and BLI values calculated from a FWD deflection survey on the N2-14 from Keiskamma River to Green River, which is currently under rehabilitation investigation. Since the pavement has a granular base, the benchmarking ranges of LLI, MLI and BLI for a granular base pavement were applied (see table 3) and are shaded in the associated colours of **sound**, **warning** and **severe**.

It is best to start with the pavement response and relative structural condition interpretation from the bottom upwards. The LLI benchmarking results show that the subgrade is in a sound structural condition for a 40 kN FWD load in the indicated section of the pass where there is rockbed. This section can serve as reference. There is variation over the rest of the road length owing to confirmed subgrade variations, such as clay, which peak in the severe zone. The MLI values over the same pass section show that the structural condition of the sub-base is also sound to warning. Where the subgrade support shows lack of structural support, for example in the clay sections, the structural

Figure 3 Typical surface moduli plots for pavement structures (Ullidtz 1987)



condition of the sub-base is also severe owing to lack of support. However, the BLI benchmarking shows that the base layer is increasingly drifting into the warning condition over large sections of the pass.

The surveyed visual condition rating over this pass section was mostly warning and severe owing to cracking, potholing and rutting. The distress thus observed therefore originates largely from the suspect base layer and, to a lesser extent, from the sub-base. The remaining section of the road can easily be interpreted in the same fashion. As illustrated, the cause of distress can be established without detailed knowledge of layer thicknesses, and limited as-built information on the base type can yield early, strong diagnostic analysis of the cause of distress in a pavement structure by applying deflection bowl parameters in this benchmarking fashion.

The plotting of cumulative sum of differences of deflection bowl parameters is also normally done to determine uniform sections in a more comprehensive way. In this way individual deflection bowl parameters or combinations thereof can be used to identify such uniform sections (Jordaan 1997). Thus the deflection bowl parameters further enhance uniform section identification as well as identification of sections needing more detailed investigations. This approach has been demonstrated elsewhere (Horak & Emery 2006).

THE CONCEPT OF SURFACE MODULUS

The deflection of the subgrade typically contributes between 60 % and 80 % of the centre deflection (D_0) directly under the load (Ullidtz 1987). The load is normally spread from the top layers to the subgrade through load transfer by the layers through a cone of about 45 degrees, as shown in figure 3. In pavement structural evaluation the correct classification and determination of the subgrade strength forms the basis of any analysis and evaluation of the pavement response. The nature of the subgrade response can be further investigated by means of the surface modulus (SM).

The SM is the weighted mean modulus of the equivalent half space calculated from the surface deflection using adapted Boussinesq's equations (Ullidtz 1987). The SM directly under the point of loading at maximum deflection D_0 is calculated as follows:

$$SM_{(0)} = 2 \cdot \sigma_0 \cdot (1 - \mu^2) \cdot (a/d_{(0)}) \quad (r = 0) \quad (1)$$

The general formula for the SM at any point away from the point of maximum deflection is calculated as follows:

$$SM_{(r)} = \sigma_0 \cdot (1 - \mu^2) \cdot \left(\frac{a^2}{r \cdot d_{(r)}} \right) \quad (2)$$

Where

$SM_{(0)}$ = surface modulus at the centre of the loading plate, in MPa and $r = 0$

Table 4 Subgrade response benchmarking with surface modulus differentials

Response classification	Surface modulus differential ranges (MPa)
Stress softening	> 20
Linear elastic	20 to -20
Stress stiffening	< -20

$SM_{(r)}$ = surface modulus at a distance r from the centre of the loading plate, in MPa

σ_0 = contact stress, in MPa

μ = Poisson's ratio, usually chosen as 0,35

a = radius of the loading plate, in mm

$d_{(r)}$ = deflection at distance r , in mm

r = radial distance from the centre of loading, in mm

SM can be calculated relatively easily with spreadsheets by using equation 1 or 2. Figure 3 illustrates typical surface moduli plots for pavement structures thus calculated and presented in graphical format in relation to the pavement structure and zone of influence. The SMs calculated at horizontal distance r is representative of the compressed material in the zone of influence below depth z . As the horizontal distance increases, a point is reached where only the subgrade falls within the zone of influence and the surface moduli thus calculated only reflect the moduli of the subgrade material.

Ullidtz (1987) determined that the gradient of the SM plot over approximately the distance defined by zone 2 and zone 3 of the deflection bowl (see figure 1) can be used to identify whether the subgrade shows stress softening behaviour, stress hardening behaviour or linear elastic behaviour (see figure 3). The subgrade response can therefore be benchmarked in the fashion suggested for the deflection bowl parameters and thus enhances the benchmarking procedure by improved description of the subgrade response and enables improved detail in subsequent focused analyses. This can be done by calculating and classifying the surface modulus differential (SMD), which is linked to the subgrade response. The subgrade SMD is easily calculated by the difference between the SM at 600 mm and that at 1 200 mm. Therefore the value of the subgrade SMD can be used as indicator of the SM gradient over zones 2 and 3 previously described. In table 4 ranges of the SMD are shown to benchmark the subgrade response as either **stress softening** behaviour, **stress stiffening** behaviour or linear elastic behaviour.

Figure 4 Subgrade response benchmarking of main runway of Bloemfontein International Airport on the centre line (40 kN)

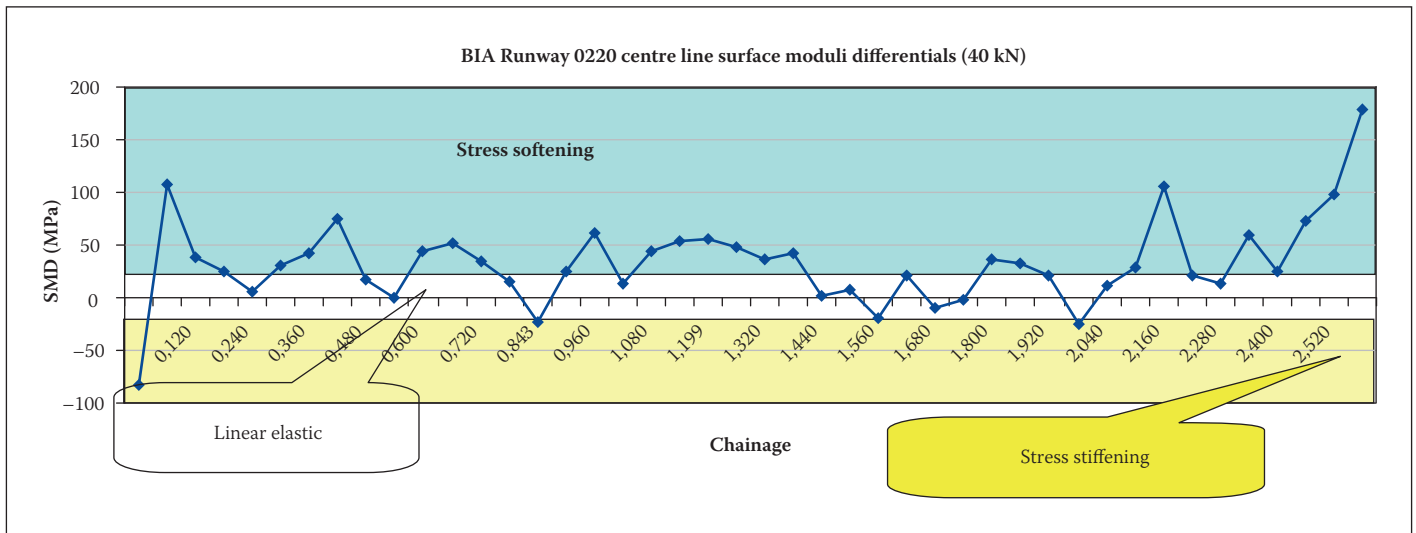


Figure 5 Example of data set used for correlation between surface modulus and middle layer index

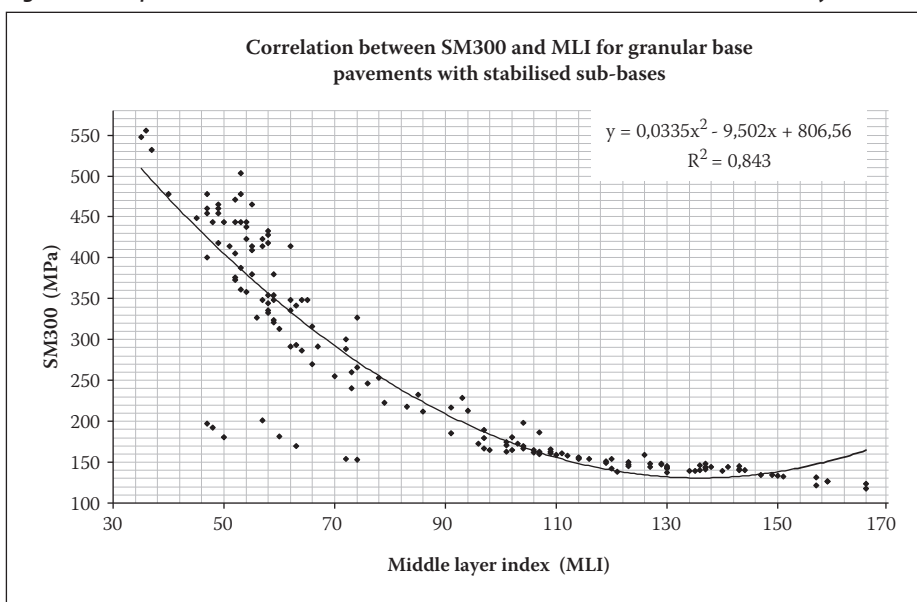


Table 5 Zone 1 surface moduli linked correlations for granular base pavements

Fitting of polynomial equation ($y = ax^2 + bx + c$) in zones 1, 2 and 3 (for $x = \text{BLI}$)								
	Granular bases with granular sub-bases				Granular bases with stabilised sub-bases			
y	A	b	c	R ²	a	b	c	R ²
SM ₀ (zone 1)	0,006	-4,905	1 182,9	0,95	0,035	-15,413	1 964,1	0,89
SM ₃₀₀ (zone 2)	0,012	-4,778	1 182,9	0,95	0,0335	-9,502	806,56	0,84
SM ₆₀₀ (zone 3)	0,061	-9,940	533,53	0,86	0,168	-20,843	767,34	0,87

SUBGRADE SURFACE MODULUS BENCHMARKING DEMONSTRATION

In figure 4 the application is shown for the centre line of the main runway of Bloemfontein Airport during a rehabilitation investigation. The FWD survey, done with a 40 kN load on the centre line, was used to calculate the SM values at the off sets of the geophones described earlier. The SM values obtained were

then used to calculate the subgrade-related SMD values for zone 3, as defined above, and are graphically represented versus distance. The subgrade response criteria defined in table 4 (stress stiffening, linear elastic or stress softening) were superimposed in colour bands to enhance the benchmarking.

It is known that Bloemfontein Airport has a silty, clayey subgrade and this subgrade

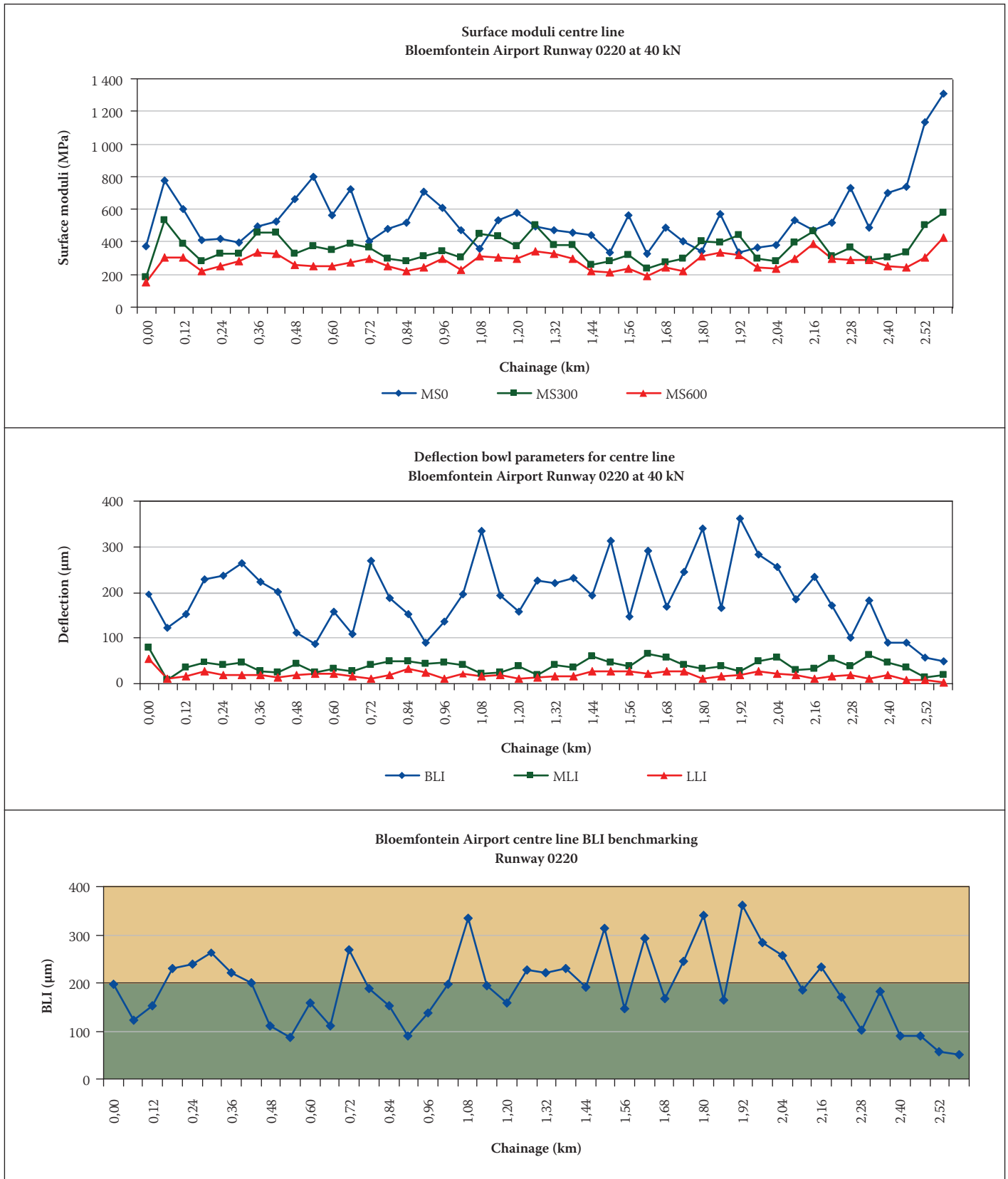
response benchmarking with the surface moduli differentials confirmed that the larger part of the runway shows stress softening, as would be expected from such a clayey subgrade. The stress softening response was also observed more intensely with the FWD survey results at the higher loads used in the survey, as would be expected from a stress softening response in situations of higher stress. This information proved to be valuable in the subsequent detailed mechanistic analyses of the subgrade response higher wheel loads. Classifying and characterising the subgrade is the departure point for a thorough structural analysis of a runway pavement structure.

DEFLECTION BOWL PARAMETERS CORRELATIONS WITH SURFACE MODULI

SM values can be used to evaluate structural strength more directly for the various zones described in figure 1. In order to validate this approach, deflection bowl parameters determined from the data base of measured deflection bowls for granular base pavements (see figure 1) were correlated with calculated surface moduli. These correlations were done for each zone and linked deflection bowl parameter separately for the data set for granular base pavements originally analysed by Maree and Bellekens (1991).

In figure 5, a sample of the granular base pavements with cemented sub-bases data set is shown in the correlation between MLI and SM₃₀₀ with the regression function and correlation coefficient (R²) indicated as demonstration. In table 5 the SM₀, SM₃₀₀ and SM₆₀₀ calculations for zones 1, 2 and 3 respectively are correlated with BLI, MLI and LLI respectively. The polynomial equation fitted to the data showed that very good correlation coefficients (R² values) were obtained for all types of granular base for these zone-specific

Figure 6 Deflection bowl and surface moduli comparison for Bloemfontein Airport Runway 0220



correlations. It would therefore be possible to use SM_0 , SM_{300} and SM_{600} in a benchmarking fashion instead of BLI, MLI and LLI.

No criteria can be set for these surface moduli derived values since only a small sample of pavement types has been correlated, but even just the plotting of any of these values versus distance surveyed can provide relative values for identification of

relative weak or strong points in the base and surface layer combination.

COMPARISON OF DEFLECTION BOWL PARAMETERS AND SURFACE MODULI DEMONSTRATION

In figure 6 the deflection bowl parameters (BLI, MLI and LLI) are shown on the same

horizontal scale as the surface moduli (SM_0 , SM_{300} and SM_{600}) that correlate with the respective deflection bowl zones 1, 2 and 3. The various deflection bowl parameters and surface moduli are inverse values. By way of demonstration it can be pointed out that BLI and SM_0 clearly vary inversely over distance. This basic inverse relationship could also be deduced from the relationship shown in the

example of regression analysis in figure 5. From this graphical comparison it is possible to use the SM values to indicate that the base and surface layers (zone 1) are not only highly variable, but also relatively low. The SM_{300} and SM_{600} values, on the other hand, are relatively uniform even though they are low. The BLI, MLI and LLI can be further benchmarked as individual layers (only BLI is shown), which confirms that the base layer varies between a warning and sound condition state while the subbase and subgrade layers are mostly sound. This comparison in figure 6 serves to show that SM values can be used to help identify and pinpoint the probable cause of distress in the pavement structure as being in the base and surface layers. This was confirmed by means of the same three-tiered visual survey condition rating that helped identify specific spots of failure in the base and surface layers.

CONCLUSIONS

Modern non-destructive survey equipment like the FWD can accurately measure the elastic response of the entire deflection bowl. This enables the use of the entire deflection bowl in either empirical or theoretically based (mechanistic) analysis procedures of pavement structures.

Correlations between a number of deflection bowl parameters and mechanistically determined structural evaluations of a number of pavement types offer the possibility to use these parameters in a semi-ME fashion to analyse pavements. The parameters can also be used in a complementary fashion with visual surveys and other assessment methodologies to describe pavement structural layers as sound, warning or severe in respect of their structural capacities and behaviour states.

This benchmarking approach is based on the premise that specific deflection bowl parameters correlate with three distinct zones on the deflection bowl, as follows:

- The RoC and BLI correlate well with the inner zone of positive curvature (zone 1)
- The MLI correlates well with the middle zone of curvature inflection (zone 2)
- The LLI correlates well with the outer zone of reverse curvature (zone 3)

Using this benchmarking methodology with the associated visual condition rating helps to accurately identify uniform sections and pinpoint the cause of structural distress, often seen only as various forms of surface distress, and helps to explain the possible

mechanism of deterioration. It enables the investigator to focus subsequent field and laboratory testing and sampling on such distressed areas when conducting further detailed investigations.

A previous correlation study was enhanced by correlating deflection bowl parameters with calculated surface moduli for granular base pavements. The SM can be calculated by means of an adaptation of Boussinesq equations that represent structural values of an equivalent elastic half space. These calculations (of the BLI, MLI, LLI and SM) can be done on a spreadsheet with ease without doing complicated modelling and back-analyses. Surface moduli thus calculated correlated very well with the related zones and linked deflection bowl parameters.

The use of the proposed three-tiered condition rating, together with the same approach for visual surveys of flexible pavement structures, enhances the identification of cause and effect of structural failure in such pavement structures. This benchmarking approach therefore enhances focused, efficient and detailed rehabilitation investigations and analyses and does not require immediate sophisticated back-analyses, layer thicknesses and detailed material information. The approach has value for detailed project level investigations, but has proven to be useful also at the network level of PMS in South Africa.

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