# FALLING WEIGHT DEFLECTOMETER BOWL PARAMETERS AS ANALYSIS TOOL FOR PAVEMENT STRUCTURAL EVALUATIONS

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## ABSTRACT

The falling weight deflectometer (FWD) is used world wide as a well established and valuable non-destructive road testing device for pavement structural analyses. The FWD is used mostly for rehabilitation design investigations and for pavement management system (PMS) monitoring on a network basis. On project level investigations, both design charts and mechanistic approaches using multi-layered linear elastic theory and back-calculation procedures are often used to provide structural evaluations and rehabilitation options. As an alternative to this a semi-mechanistic semi-empirical analysis technique has been developed in South Africa whereby new deflection bowl parameters measured with the FWD used to give guidance on individual layer strengths and pinpoint rehabilitation needs. This approach is fully suited to supplementary analysis of FWD data in the Australian design systems, and overcomes some of the limitations of the curvature parameter. This paper briefly describes the current practice and basis of this use of deflection bowl parameters, and illustrates the use with a current pavement rehabilitation project underway in South Africa.

## INTRODUCTION

Deflection measurements of pavement structures are used to do structural analyses for the purpose of rehabilitation design as well as for network monitoring of pavement networks. The older equipment like the Benkelman beam and La Croix deflectograph were used extensively in the past and various empirical relations were developed for analysis and overlay design by organisations like Shell, the Asphalt Institute, and TRRL. In most cases only the were utilised and the shape of the deflection bowl and the significance of its relationship with the pavement structural response were basically ignored and wasted. Other design methods such as Austroads (1992) used maximum deflection and the Australian Curvature Function ($D_0$ – $D_{200}$). The improvement of non-destructive deflection measuring devices resulted in the ability to measure the whole deflection bowl accurately, and enabled use of whole deflection bowl in structural analysis of roads and pavements (Horak, 1988).

The extensive use of the modified Benkelman beam, the road surface deflectometer (RSD), with accelerated pavement testing (APT) devices, like the heavy vehicle simulator (HVS) in South Africa, coupled with the use of the in depth deflection measurements with the multi-depth deflectometer (MDD), helped to give credibility to the back-calculation of elastic moduli with various multi-layered linear elastic computer models. The extensive test programmes of the HVS in South Africa helped to correlate such back-calculated elastic moduli with pavement performance and deterioration modelling and helped to increase the credibility and use of back-calculated elastic moduli derived from surface deflection measurements. (Horak, et al, 1992).

A brief overview of the evolutionary use of the full deflection bowl is given to describe the rationale behind the development of new deflection bowl parameters in a well established, semi-mechanistic-empirical analysis procedure. A well documented current rehabilitation project is used to demonstrate the value of these parameters in structural analysis and rehabilitation design.

## APPRECIATION OF THE FULL SURFACE DEFLECTION BOWL

When a pavement deflects under a load, the influence of the load can extend over an area measurable 1 to 2 meters away from the point of loading in three dimensions. This is illustrated in Figure 1 for a uniform circular and truck dual axle loading situation. This deflected area tends to form a circular deflected indentation called a deflection bowl. The size and shape of the deflection bowls vary and depend on different factors such as pavement composition and structural strength, size of load contact area, load magnitude and duration of loading, the measuring device used, temperature, etc. (Horak, 1987 and 1988 and Lacante, 1992).

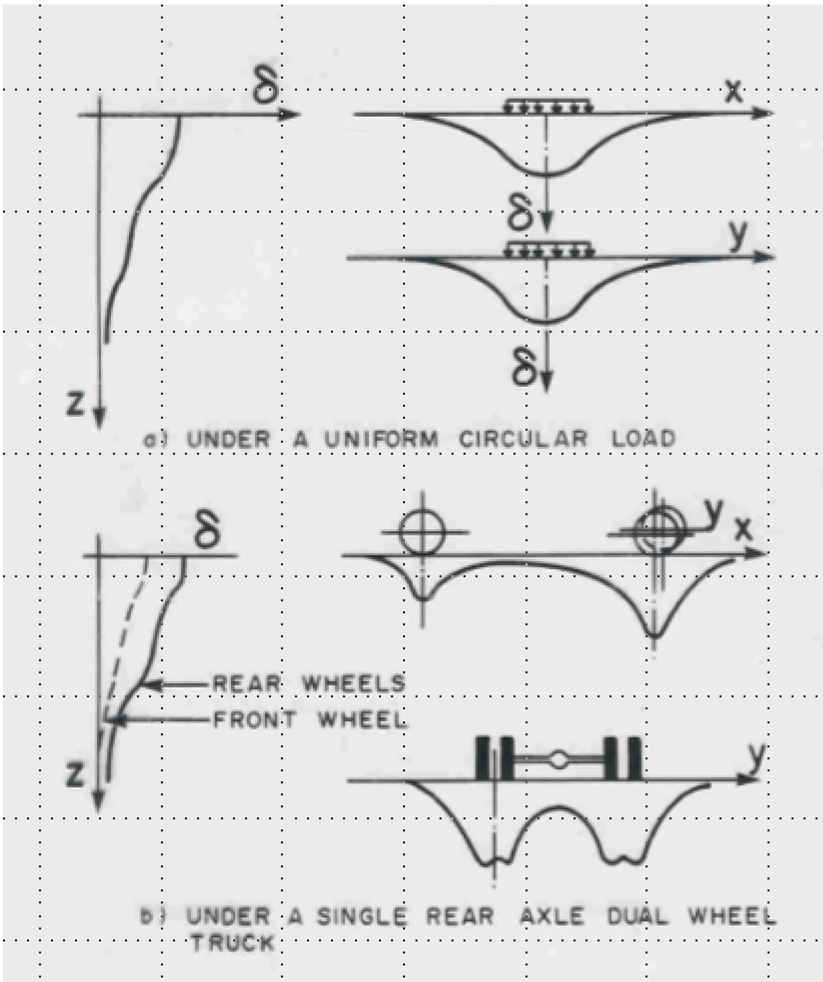


**Figure 1. Illustration of deflection bowl shapes under various forms of loading**

Prior to the arrival of electronic measuring equipment the deflection bowl was measured mostly with the Benkelman beam. It measured maximum “re-bound” deflection and resulted in various empirical design and analysis procedures based solely on this single point on the deflection bowl. These measuring techniques had a number of shortcomings. The Benkelman beam required a loaded truck with a standard axle to position over the point of the beam between the dual tyres and pull away to register the “re-bound” deflection measurement. This rebound measurement included plastic deformation components due to the static loading situation before the truck moved away from the measuring point. One of the side-effects was the “pinching” effect which occurred between the dual wheels as illustrated in Figure 1. This effect is pronounced on soft bases and warm asphalt surfacings (Horak, 1988 and Dehlen, 1961).

The wealth of information in the rest of the deflection bowl went virtually wasted in analysis methods developed in the early 1950s and 1960s. However, Dehlen (1961) used the Benkelman beam to record the deflection at 75mm intervals to plot the whole deflection bowl. Particular attention was given to the detail of the inner 600mm close to the point of maximum deflection. The radius of curvature at the point of maximum deflection was obtained by determining the circle which best fit to the curve over the central 250mm (10inches). Dehlen (1962) noted that a circle fitting the deflected surface in the field is an approximation of either an ellipse or sinusoidal or parabolic form and the error by means of this approximation with a fitted circle was less than 5%. The Dehlen curvature meter was subsequently developed which enabled the measurement of the curvature directly as illustrated with the original geometrical configuration of the Dehlen curvature meter in Figure 2. The relation between curvature and differential deflection may be deduced by simple geometry by fitting an appropriate curve to the three points on the road surface defined by the instrument.

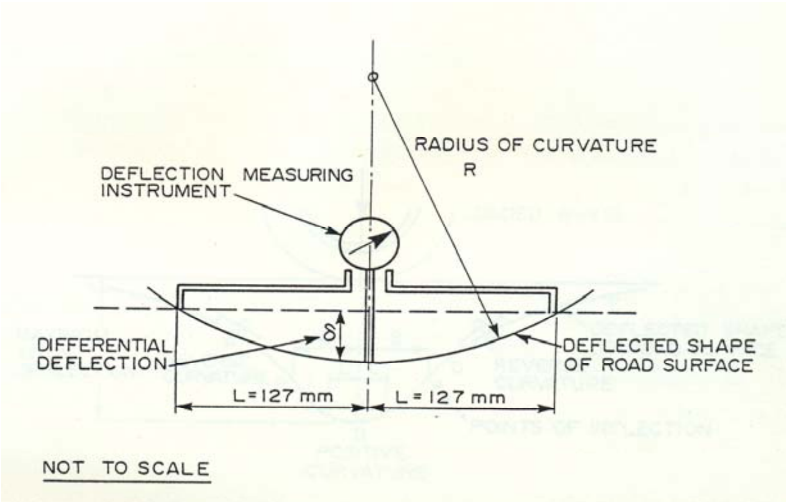


**Figure 2: Schematic illustration of the original Dehlen curvature meter geometry**

In the mid to late 1980s the Falling Weight Deflectometer (FWD) became the new electronic deflection measuring tool of choice which could simulate a moving wheel load, measure elastic response and the critical points on the whole deflection bowl up to a distance of 1.8m to 2m away from the point of maximum deflection or loading (Coetzee et al, 1989). This measurement of the whole deflection bowl led to the definition of various deflection bowl parameters which described various aspects of the measured deflection bowl. In Figure 3 the deflection bowl under a dynamic load, such as the FWD, is shown superimposed on a typical South African pavement structure profile with a thin surfacing layer.

The derivation of the three new deflection bowl parameters; Base Layer Index (BLI), Middle Layer Index (MLI) and Lower Layer Index (LLI), is illustrated on the same diagram. Over and above their descriptive names their respective associations with various structural layers are also indicated by means of interlinking arrows.

In Table 1 various deflection bowl parameters and their formula are summarized with their association with pavement structure and structural elements. There are other parameters, but these have been found to have good correlations with the relevant pavement structural condition and individual pavement layer associations (Horak, 1988).

**Table 1: Deflection Bowl Parameters**

| **Parameter** | **Formula** | **Structural indicator** |
|---|---|---|
| 1 .Maximum deflection | $D_0$ as measured | Gives an indication of all structural layers with about 70% contribution by the subgrade |
| 2a Australian Curvature Function | $CF=D_0-D_{200}$ | Gives an indication of the structural condition of the surfacing and base |
| 2b. South African Radius of Curvature (RoC) | $RoC=\dfrac{(L)^2}{2D_0(1-D_{200}/D_0)}$<br>Where L=127mm in the original Dehlen curvature meter and 200mm for the FWD | Gives an indication of the structural condition of the surfacing and base condition |
| 3.Base Layer Index (BLI) | $BLI=D_0-D_{300}$ | Gives an indication of primarily the base layer structural condition |
| 4.Middle Layer Index (MLI) | $MLI=D_{300}-D_{600}$ | Gives an indication of the subbase and probably selected layer structural condition |
| 5. Lower Layer Index (LLI) | $LLI=D_{600}-D_{900}$ | Gives an indication of the lower structural layers like the selected and the subgrade layers |

The South African radius of curvature (item 2b of Table 1) has been adjusted for the standard settings of a FWD by increasing the central area over which the circle is fitted from 250mm to 400mm, which uses deflection values at 0 and 200mm. The use of these deflection bowl parameters in the evaluation of the structural capacity of a pavement has subsequently been suggested and used by several researchers (Maree and Bellekens, 1991, Rohde and van Wijk, 1996 and Jordaan, 2006). Note that the Australian and South African curvature functions are calculated differently; the South African one better fits the sinusoidal geometry found in the deflection bowl by the Dehlen (1962) research.

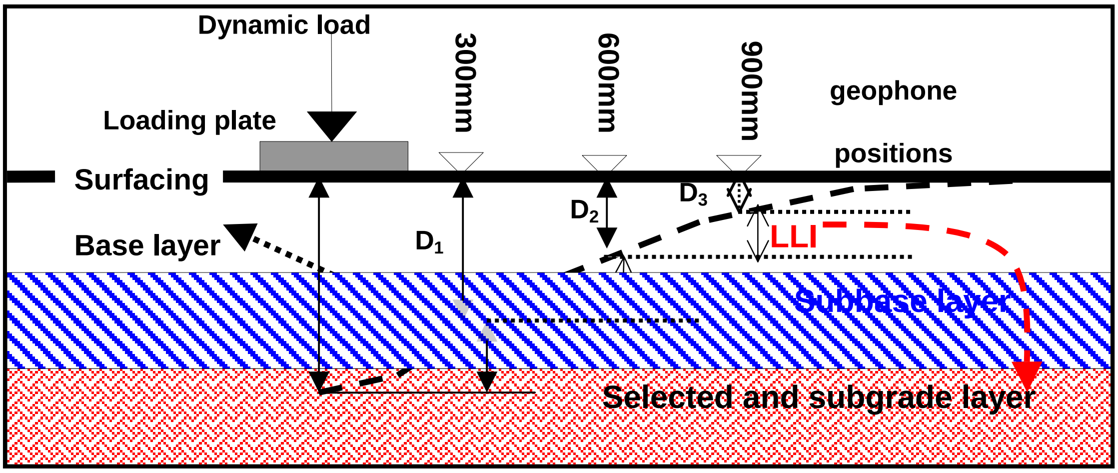


**Figure 3. Bowl parameters and their associations with the pavement structure**

Maree and Bellekens (1991) analysed various pavement structures (granular, bituminous and cemented base pavements) as measured with the FWD. Pavement structures were analysed mechanistically, remaining lives determined and correlated with measured deflection basin parameters. This enabled them to develop a correlation between the new deflection bowl parameters and remaining life (expressed in terms of standard or equivalent 80kN axle repetitions - E80s in the South African systems and ESAs in the Australian system). These are shown in Figure 4 for three distinctively different pavement types namely; granular, bituminous and cemented base pavements.

The new deflection bowl parameters enable the rehabilitation designer to look at the contribution of each layer to the pavement performance, and represent a step forward from using maximum deflection and radius of curvature. They are easily calculated from standard FWD analysis results, and give an improved insight into the pavement. They have been included in the TRH12 guidelines for rehabilitation design and analysis in South Africa (CSRA, 1997).

## STRUCTURAL CONDITION INDICATIONS USING THE NEW DEFLECTION BOWL PARAMETERS

Pavement structural analysis process typically uses a multi-faceted approach with some or all of the following: visual surveys, instrument surveys (such as FWD and riding quality), field material sampling, laboratory testing, etc. What the new deflection bowl parameters do is act as structural condition indicators and allow the deflection bowl parameters from the FWD to be used as a filtering approach. This is done by calculating them over the length of the pavement, and using them to identify and pinpoint structural deficiencies in various layers and locations. Deficiencies can then be further investigated.

Maximum deflection alone is a blunt instrument as other pavement layers often filter this maximum deflection value, and it does not facilitate pinpointing the layer of the structural deficiency in the total pavement structure. The various curvature parameters work less effectively with FWD data, because they can be confounded by the proximity between the edge of the loading plate and the geophone at 200mm offset. This may explain some of the problems estimating allowable loading from FWD curvature because it varies markedly with overlay thickness (Austroads, 2004b), which had led to the exclusion of predicted design curvatures for asphalt overlays less than 40 mm thick in the Austroads 2004 Guide procedures. The new deflection bowl parameters offer an improvement on curvature.

The new deflection bowl parameters allow a three level structural condition rating to be applied (sound, warning and severe) for the first pass of analysis of the FWD data. In Table 2 the deflection bowl ranges for a granular base pavement are summarized for this three level condition rating. Ranges also exist for radius of curvature, but are not shown here because of the limitations of curvature with FWD testing.

**TABLE 2: Condition rating criteria for deflection bowl parameters for granular pavements designed for $3x10^6$ standard 80 kN axles**

| ***Structural condition rating*** | **Deflection bowl parameters** | | | |
|---|---|---|---|---|
| | **$D_0$ ((µm)** | **BLI ((µm)** | **MLI ((µm)** | **LLI ((µm)** |
| **Sound** | <400 | <200 | <100 | <55 |
| **Warning** | 400-750 | 200-500 | 100-200 | 55-100 |
| **Severe** | >750 | >500 | >200 | >100 |

## DEFLECTION BOWL PARAMETERS FOR OTHER BASECOURSE TYPES AND TRAFFIC CLASSES

The new deflection bowl parameters have been derived from the work of Maree and Bellekens (1991) and Jordaan (2006), and can be linked to traffic levels and various pavement base types as shown in Figure 4. This shows various remaining lives expressed in terms of equivalent 80kN standard axles (E80s) classes for granular, asphalt and cemented base pavements.

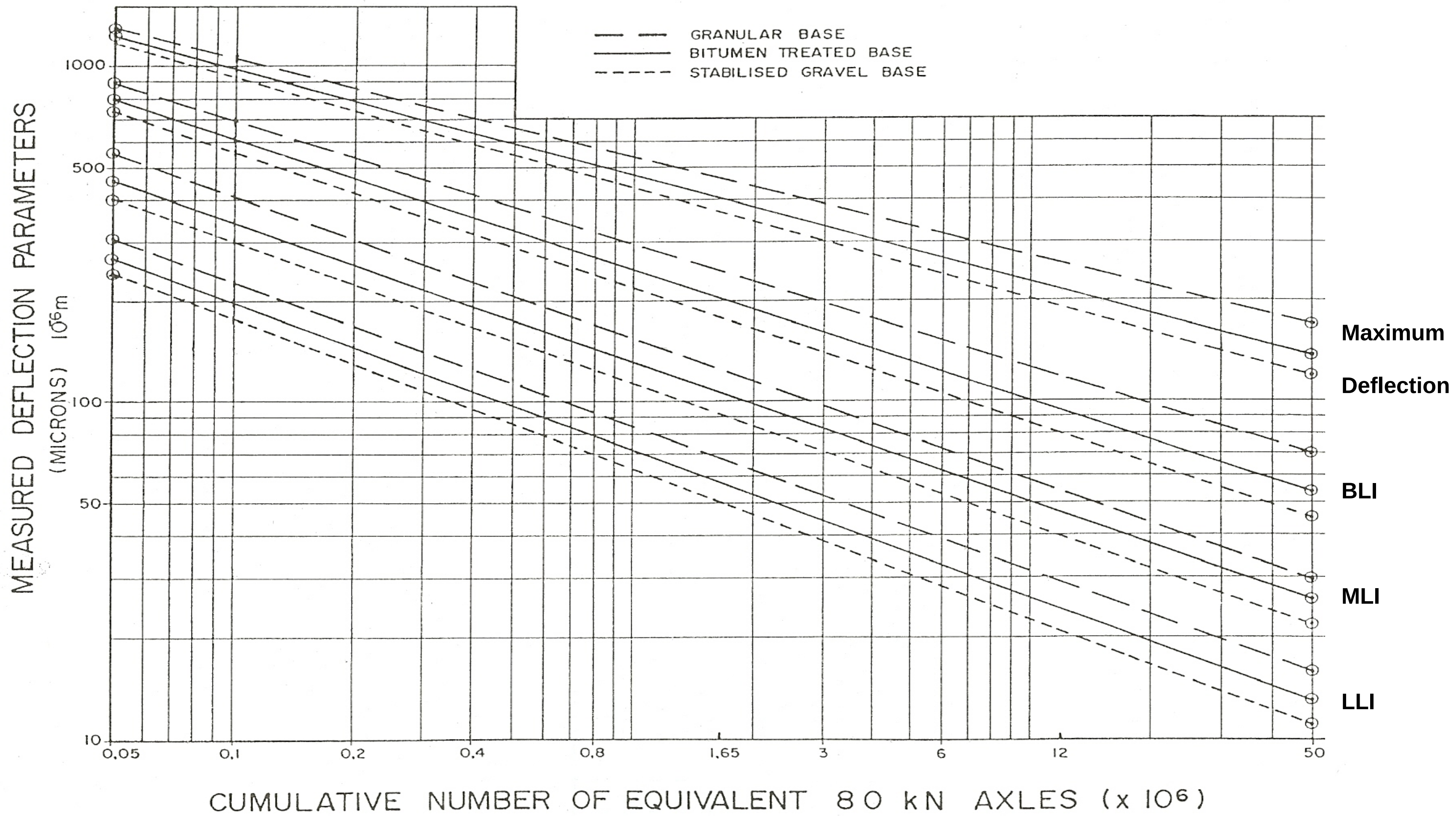


**Figure 4. Correlation between deflection bowl parameters and remaining life** (Source: Maree and Bellekens, 1991)

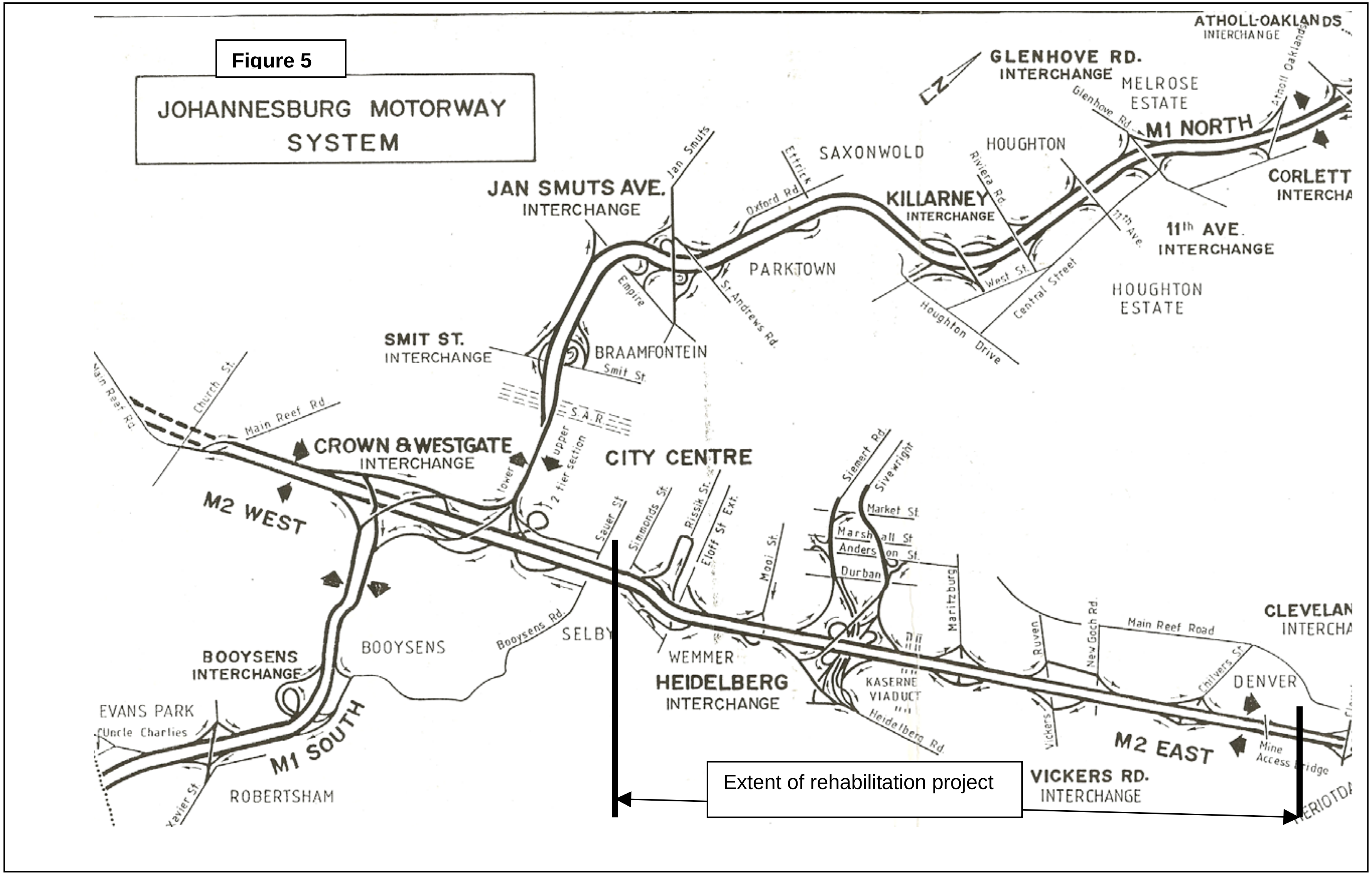
Figure 5
JOHANNESBURG MOTORWAY SYSTEM
ATHOLL-OAKLANDS INTERCHANGE
GLENHOVE RD. INTERCHANGE
MELROSE ESTATE
M1 NORTH
CORLETT INTERCHA
SAXONWOLD
HOUGHTON
KILLARNEY INTERCHANGE
11th AVE. INTERCHANGE
JAN SMUTS AVE. INTERCHANGE
PARKTOWN
HOUGHTON ESTATE
SMIT ST. INTERCHANGE
BRAAMFONTEIN
CROWN & WESTGATE INTERCHANGE
CITY CENTRE
M2 WEST
BOOYSENS
SELBY
WEMMER
HEIDELBERG INTERCHANGE
KASERNE VIADUCT
CLEVELAN INTERCHA
DENVER
BOOYSENS INTERCHANGE
EVANS PARK
ROBERTSHAM
M1 SOUTH
M2 EAST
VICKERS RD. INTERCHANGE
Extent of rehabilitation project

# ILLUSTRATION OF THE USE OF DEFLECTION BOWL PARAMETERS IN STRUCTURAL ANALYSIS

The best way to illustrate the application of the deflection bowl parameters is by means of data from a rehabilitation project. In Figure 5 the motorway system of Johannesburg is shown. A section of this multi-lane road is currently under rehabilitation as indicated on the plan shown in Figure 5. This 10km motorway section carries in excess of 70 000 vehicles per day per direction and is mostly running at capacity on four lanes dropping to three lanes in the eastwards direction. Some sections are elevated road structures with a number of busy interchanges in between. The as built pavement structure was a 200mm granular base pavement with a 40 to 60mm asphalt premix surfacing. This is all supported by selected and subbase layers of mine sand. The pavement structure had originally been rehabilitated 20 years ago and then again nearly ten years later; this second repair at 10 years ago had reconstructed the basecourse with good quality material. In most cases the rehabilitation involved recycling of base and surfacing layers with an emulsion treatment. On the westwards direction asphalt base replacement with large aggregate mix base (LAMB) was done (Horak et al, 1994).

In 2005 this section of the M2 Motorway, under the jurisdiction of the Johannesburg Roads Agency (JRA), had to be rehabilitated again. A very good record existed of the pavement structures and history of maintenance and rehabilitation. This makes this section of motorway ideal to demonstrate the value of the use of the deflection bowl parameters as part of the detailed condition assessment for the rehabilitation design of this complex high traffic volume road. FWD surveys were done on the slow and middle lanes of this multi-lane motorway at 100m intervals in both directions. For the purposes of demonstration only the FWD results for the slow lane in the eastwards direction are used and shown here. The slow lane of the M2 eastwards direction has a granular based pavement structure and therefore criteria for granular base pavements will be used to demonstrate the use of these deflection bowl parameters in the structural analysis.

## Determination of homogeneous sub-sections

Simple statistical procedures are very effective to discriminate homogeneous sub-sections within a larger section. A homogeneous sub-section is defined as a section where the deflections and so the flexural stiffness are more or less constant. These can be determined by means of the method of the cumulative sums. The cumulative sums are calculated in the following way. First of all the mean of a variable over the entire section is calculated (e.g. the mean of the maximum deflection). Then the difference between the actual value of the variable and the mean is calculated. Next these differences are summed and plotted (Figure 6). The points of inflection typically represent changes in sub-section (Molenaar, 2003). This is a simplified version of the approach currently used in South Africa as promoted by Jordaan (2006)

(Jordaan and de Bruin, 2003), but serves to illustrate the value of using the deflection bowl parameters in this fashion. The position of the elevated road (bridge) structures are indicated and outside those, at least 9 different homogeneous sub-sections can be discerned in this way as a first indication of variable structural capacity over the length of road.

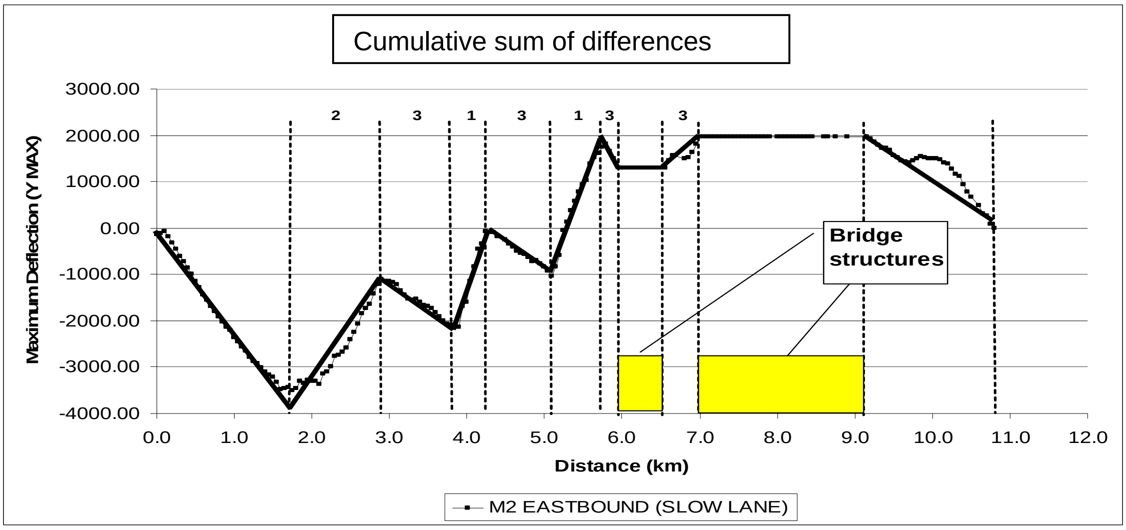


**Figure 6. Determination of homogeneous sub-sections using maximum deflection and cumulative sum of differences on M2 Motorway Johannesburg**

# Applying the new deflection bowl parameters

## Subgrade

The lower layer index (LLI) values were calculated and plotted along the length of the road (Figure 7), together with sound/warning/severe limits appropriate for that class of traffic (from Figure 4). They correlated well with the structural condition of the selected subgrade and the subgrade layer. The sections where the LLI falls in the severe condition range are circled in Figure 7 and coincides with two of the uniform sections identified in Figure 6. These are sections which clearly have subgrade and selected layer weaknesses.

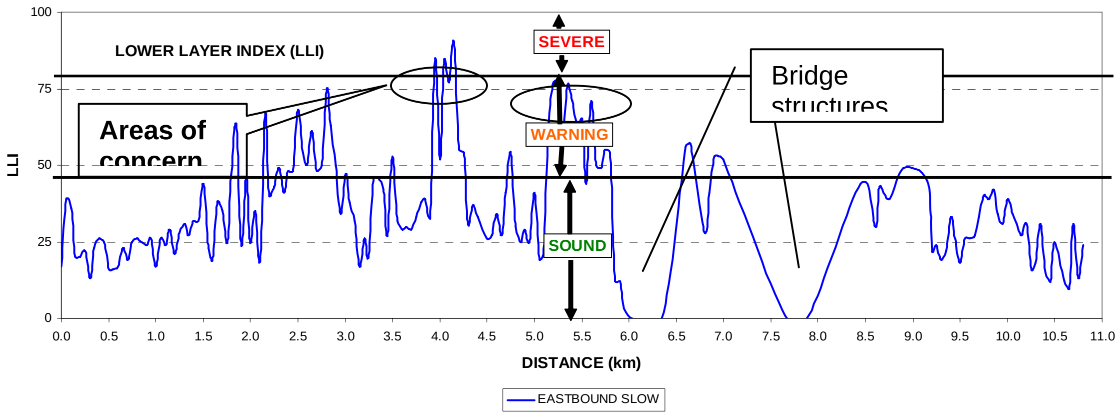


**Figure 7. Lower layer index evaluation on M2 Motorway Johannesburg**

The visual condition surveys were overlayed on another drawing (not shown here for reasons of space) and the weak sections had long undulations and surface deformations which are characteristic of subgrade failure. Riding quality survey results (not shown here) also confirm the effect of such undulations. Other sections in the warning condition also show the same early signs of failure of the same type of undulations.

## Subbase

The middle layer index (MLI) values were calculated and plotted along the length of the road (Figure 8). The same sections of concern picked up in the subgrade analysis are also highlighted in the subbase layers, most probably due to the lack of support from the layers below this subbase, namely the selected and subgrade layers. Over and above the undulations linked directly with the subgrade the cracked visual condition of these failed sections confirm the possible source of the distress as not just limited to the subgrade.

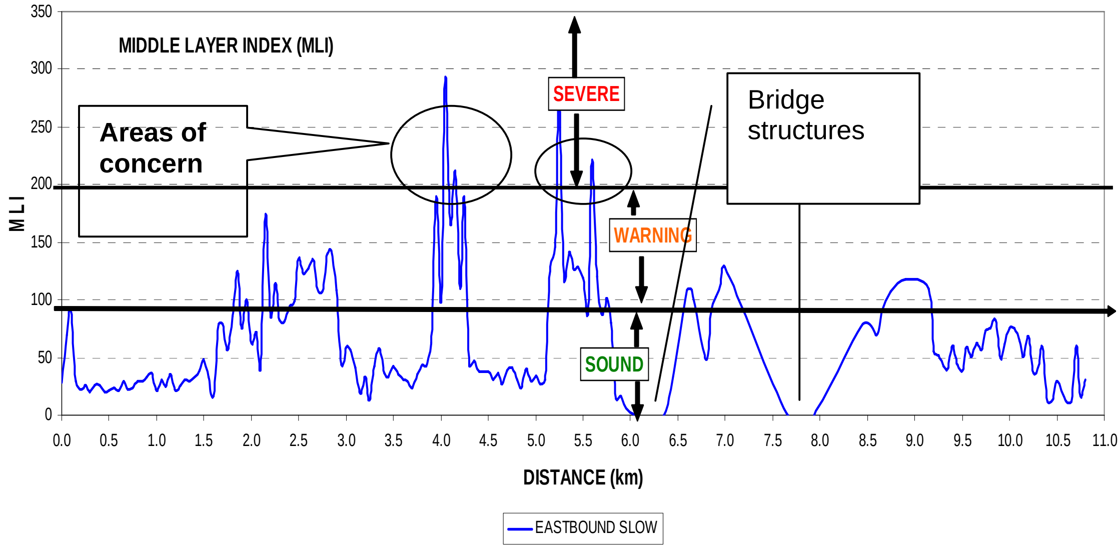


**Figure 8. Middle layer index evaluation on M2 Motorway Johannesburg**

## Base layer and surfacing

The base layer index (BLI) values were calculated and plotted along the length of the road (Figure 9). BLI values correlate well with the structural condition of the base layer, and although the BLI values shown in Figure 9 coincide with the indications of the other structural layer deficiencies reflected from below, the structural condition rating of the base layer does not reach into the severe condition. Therefore it is likely that even though the granular base layer has several sections in the warning condition, it is in a process of deterioration due to the lack of support from below. The sections peaking into the warning condition also showed visual signs of cracking (block and crocodile) in isolated areas. It should also be noted that this base was rehabilitated in 1995. This may explain why it is standing up well despite the lack in support from underlying layers.

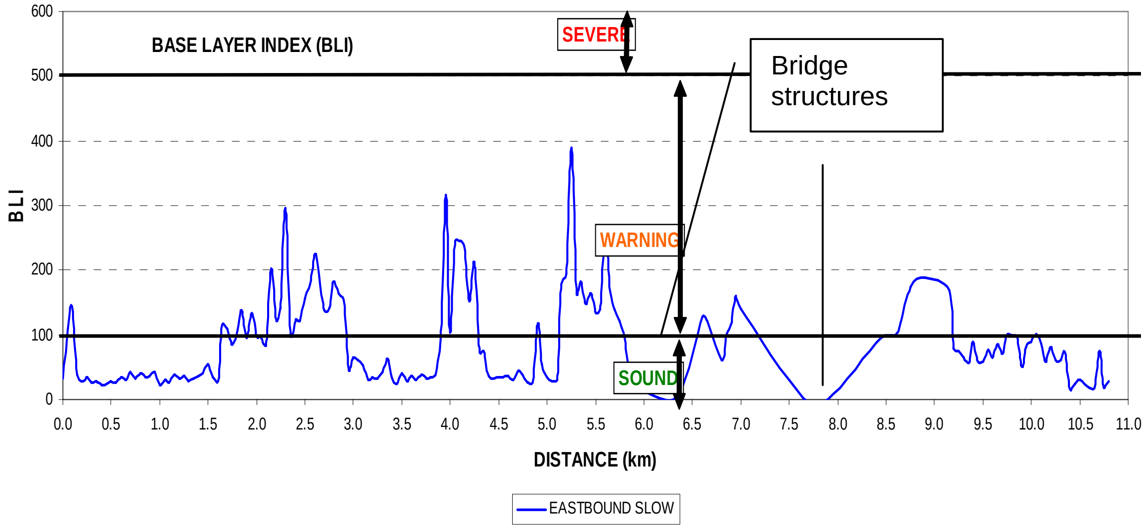


**Figure 9. Base layer index evaluation on M2 Motorway Johannesburg**

## Radius of curvature, Curvature Function and maximum deflection

The South African radius of curvature (ROC) generally gives reasonable indications of the base and surface layer structural condition, but is less reliable if the pavement structural problem is just below these layers. Like the Australian curvature function, it is potentially confounded in FWD measurements by the proximity between the edge of the 300mm diameter loading plate, and the 200mm geophone. In Figure 10 the RoC values would indicate that the majority of the road length is in a sound condition, but there are some sections in a warning condition. In this case RoC values of more than 120m correspond to sound conditions, between 40 and 120m correspond to warning and less than 40m correspond to severe conditions. These values were not included in Table 2 but are as used in TRH12 (1997). These areas of concern are also sections which show visual distress identified by the cracked state of the surfacing layer.

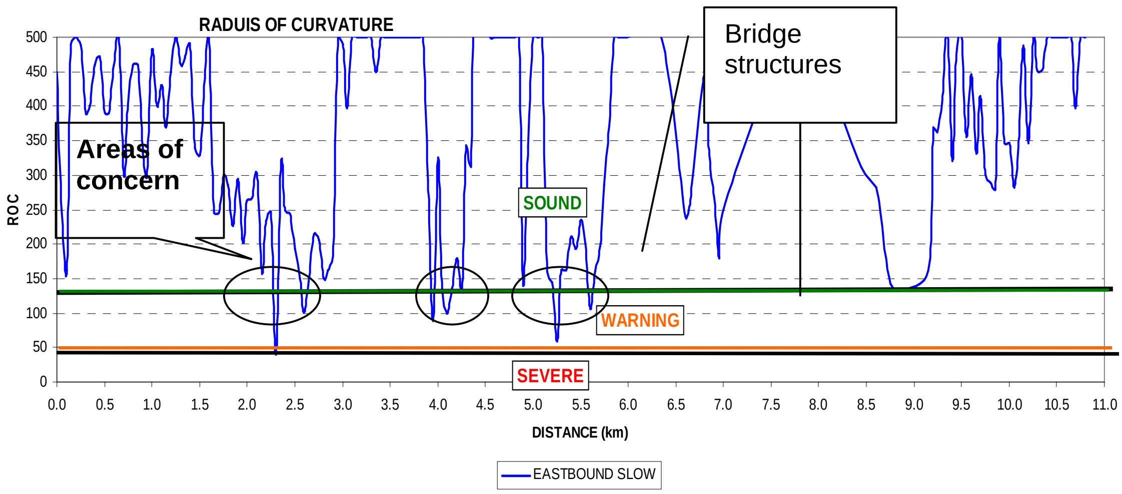


**Figure 10. South African radius of curvature evaluation on M2 Motorway Johannesburg**

The Australian Curvature Function also gives an indication of the base and surface layer structural condition, but is also problematic with FWD readings. In Figure 11 the Australian Curvature Function (CF) has been calculated and plotted versus distance on the Eastbound Slow lane. If compared with Figure 10, it correlates with South African radius of curvature and indicates problems in the same areas around km 2.5, 4 and 5.2.

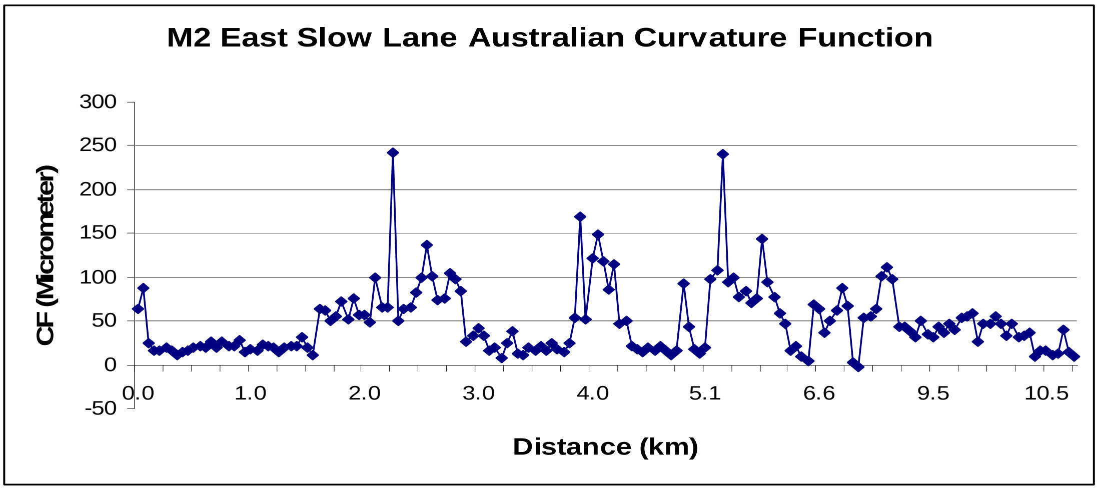


**Figure 11. Australian Curvature Function evaluation on M2 Motorway Johannesburg**

In Figure 12 the maximum deflection values were calculated and plotted along the length of the road, and they indicate that the majority of the road length is in a sound condition. There are only one or two areas which reach into the warning condition and clearly do not reflect the distress observed from the other deflection bowl parameters originating in the lower layers. With the insight from the new deflection parameters it is possible to deduce that the base layer (reconstructed 10 years ago) is cushioning or filtering the origins of distress from below.

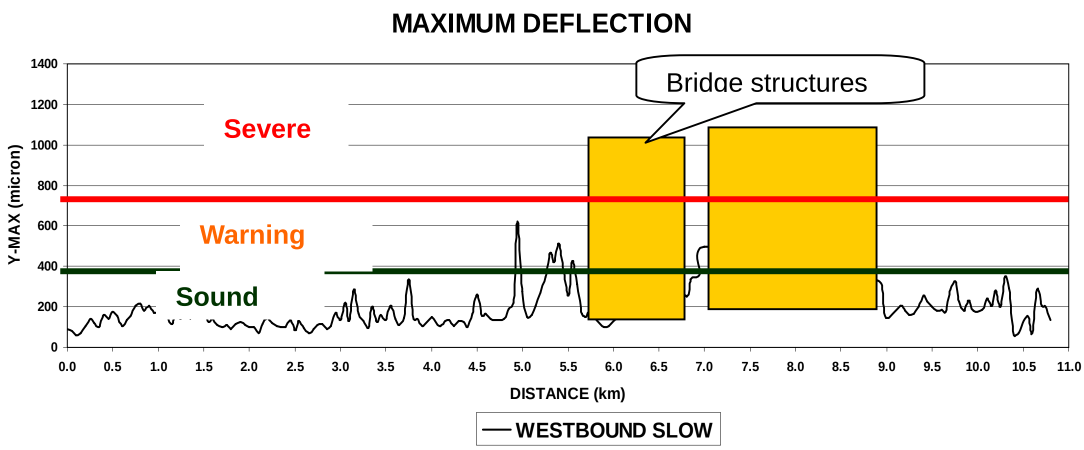


**Figure 12. Maximum Deflection evaluation of M2 Motorway**

### Comparison of rehabilitation solutions

The rehabilitation solution derived from maximum deflection and curvature would have been different to that derived from the new deflection bowl parameters. Using maximum deflection and curvature, the performance of the individual layers was masked and could not be separated out. The maximum deflection indicates that the pavement is generally structurally sound, and both curvature functions indicate that the base needs rehabilitation in some sections. The typical solution would be to do base repairs in the identified sections (using mix-in-place cement stabilisation or even full-depth asphalt), followed by an asphalt overlay. The long term effectiveness of this solution is questionable because it has not addressed the fundamental underlying weakness of the subgrade and subbase at those sections. The cement stabilised option, which is popular in South Africa, could well fail prematurely due to a lack of support.

Using the new deflection bowl parameters, both LLI and MLI have identified sections which clearly have subgrade and quite likely subbase weaknesses, and BLI indicated only a minor concern with the base. This better fits the knowledge that the base was reconstructed 10 years ago with good quality material, and might explain why this reconstruction only lasted 10 years. These lower layers need to be rehabilitated, and the process of doing so would also remediate any basecourse deterioration. Because of possible time and delay implications for deep repairs, the designer is now guided to explore alternatives such as thick asphalt overlay or mix-in-place bituminous stabilisation of the base, as well as deep reconstruction. The analysis also suggests the areas requiring further investigations such as field and laboratory testing and sampling.

## CONCLUSIONS

Modern non-destructive survey equipment like the FWD can accurately measure the elastic response of the whole deflection bowl. This enables the use of the whole 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 offers the possibility to use these parameters in a semi-empirical-mechanist fashion to analyse pavements. Such parameters can be used in a complementary fashion with visual surveys and other assessment methodologies to describe pavement structural layers as sound, warning and severe regarding their structural capacity. This technique can be used in a “sieving” action to identify structural failure and pin point it to specific layers for further detailed investigations with other assessment methodologies. The example illustrated on a high traffic volume road demonstrated the approach and value of this fuller use of the deflection bowl and associated parameters in the structural evaluation and assessment of pavements in rehabilitation analyses. In short, this “sieving” approach applied to the deflection bowl data helps to accurately identify uniform sections and helps to pinpoint the cause of structural distress, often seen as various forms of surface distress, and help to explain the mechanism of deterioration. It enables to focus on such distressed areas with further investigations such as field and laboratory testing and sampling.

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