Evaluation of airport pavements with FWD deflection bowl parameter benchmarking methodology

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ABSTRACT: Mechanistic analysis for pavement evaluation normally uses multi-layered linear elastic theory and back-calculation procedures. These procedures can have inaccuracies due to variance in assumptions and modelling approaches. A semi-mechanistic semi-empirical analysis technique is presented here whereby FWD deflection bowl parameters are used in a relative benchmarking methodology. This assesses the relative structural condition of the pavement, across its length, breadth and depth. It uses a simplified three level system of condition rating on isographs or graphs to identify the various layers and areas of various structural conditions. The system is often combined with visual survey condition to steer further detailed investigations very effectively. It has been used with success on road pavements in South Africa. This benchmark methodology has now been adapted for use on airports. A number of airport pavements in South Africa, Namibia and Australia have been analysed in this fashion in rehabilitation and structural analyses.

KEY WORDS: Pavement, airport, FWD, deflection, benchmarking, rehabilitation.

1. INTRODUCTION

Deflection measurements of pavement structures are standard non-destructive inputs to structural analyses for the purpose of rehabilitation design as well as for monitoring of airport pavement networks. Equipment like the Benkelman Beam and deflectographs (e.g. the LCPC developed La Croix) were used extensively in the past world wide, and various empirical relations were developed for analysis and overlay design by organisations like Shell, the Asphalt Institute, and TRRL (Jordaan, 1988). In most cases only the maximum deflection was utilised in the past. The shape of the deflection bowl and the significance of its relationship with the pavement structural response were largely ignored and therefore was wasted. Since the 1980s significant improvement of non-destructive deflection measuring devices resulted in the ability to measure the whole deflection bowl accurately. It also enabled an appreciation of the value of the whole deflection bowl in structural analysis of road and airport pavements (Horak and Emery, 2006).

The falling weight deflectometer (FWD) is well established as a pavement testing tool. The extensive accelerated pavement testing (APT) test programme of the Heavy Vehicle Simulator (HVS) resulted in the verification and promotion of the mechanistic-empirical design and analysis procedure in SA. The use of the multi-depth deflectometer (MDD) with the modified Benkelman Beam, the road surface deflectometer (RSD), enabled APT with the HVS to measure deflection bowls accurately in depth as well as on the road surface. This enabled back-analysis of effective elastic moduli of the various layers with great confidence and acted as stimulus for the development and subsequent confidence in the SA mechanistic design and analysis procedure (Theyse, 1996).

World wide development of back analysis procedures and associated software has happened over the past 10 to 15 years, but has run into various problems of credibility due to the uncertainties regarding material characterisation, uniqueness of measuring equipment, personal interpretations, confusion of dynamic and static response and basic material variabilities (Ullidtz, 2005).

A more simplified approach for first level analysis was developed by using more of the measured deflection bowl than merely maximum deflection. It has been shown that deflection bowl parameters can be used in a benchmarking procedure (Horak and Emery, 2006) to help identify weaker areas in pavements over length and width as well as in-depth of the pavement structure (identify structurally weak layers) to help optimise further detailed investigations. These benchmark analyses are based on simple spreadsheet calculations using the measured FWD deflection bowls without doing complicated back-analyses normally requiring complicated linear elastic layered software or finite element method analyses.

The benchmark criteria developed for road pavement structures have subsequently been used in the rehabilitation and upgrade of airport pavement structures with success. Adjustments of the benchmark criteria for the heavier contact stress situations on airport pavement structures were made from the road pavement loading situation using the linearity of elastic relationships. The use of these benchmark criteria are demonstrated by means of a number of airport pavements recently analysed in Southern Africa and Australia.

2. DESCRIPTION OF THE DEFLECTION BOWL IN TERMS OF ZONES

In Figure 1 it is shown that a deflection bowl measured under a loaded wheel can basically be described in terms of three distinct zones (Horak, 1988). In zone 1, close to the point of loading, the deflection bowl has a positive curvature. This zone will normally be within a radius not more than 300mm from the point of loading. Zone 2 represents the zone where the deflection bowl switches from a positive curvature to a reverse curvature and is often referred to as the zone of inflection. The exact position of the point of inflection in zone 2 depends on specific pavement layer structural compositional factors and zone 2 normally varies from approximately 300mm to 600mm from the point of loading. Zone 3 is furthest away from the point of loading where the deflection bowl has switched to a reverse curvature and extends to the normal road surface, i.e. where deflection reverts back to zero. Zone 3 normally stretches from approximately 600mm to 2000mm. However, the extent of this zone will depend on the actual depth of the pavement structure and is mainly dependant on the structural response of the deeper layers such as the subgrade layer.

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

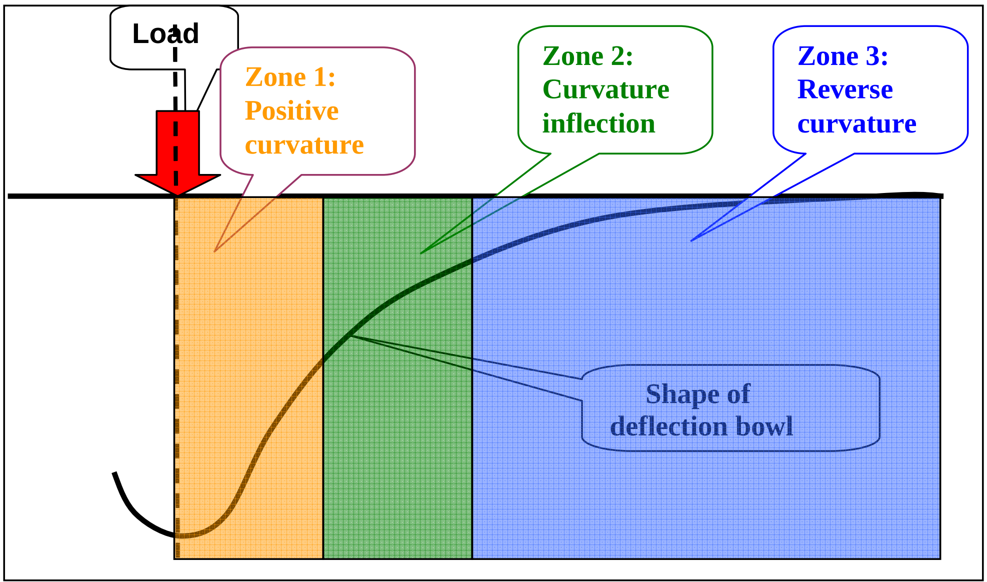

Figure 1. Curvature zones of a deflection bowl

3. DEFLECTION BOWL PARAMETERS

The Falling Weight Deflectometer (FWD) became the deflection measuring tool of choice in the mid to late 1980s in the USA and SA followed suit. The FWD can simulate a moving wheel load and measure elastic response with the whole deflection bowl up to a distance of 1.8m to 2m away from the centre point of loading. The Heavy Weight Deflectometer (HWD) follows the same principles, and both machines may be used on airport pavements. In South Africa the position of the geophones for the FWD has been standardized to measure at 0mm, 200mm, 300mm, 450mm, 600mm, 900mm, 1200mm, 1500mm and 1800mm from the centre of the load. This distribution was found to give a fair description of the whole deflection bowl. This measurement of the deflection bowl by means of the FWD led to the definition of various deflection bowl parameters which describe various aspects of the measured deflection bowl.

In Table 1 a selected number of deflection bowl parameters and their formulae are summarized as linked to the deflection bowl zones and their formulae based on the measured deflection bowls. Radius of Curvature (RoC) and Base Layer Index (BLI) have been found to correlate well with zone 1 (mostly surfacing and base layers), Middle Layer Index (MLI) with zone 2 (mostly subbase layer) and 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 are used.

Due to the closeness of the geophone at 200mm to the edge of the loading plate and associated surface disturbances observed 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 analyses methods which tended to rely on the deflection value at 200mm, e.g. Australia where a curvature ratio is calculated based on that value. (Horak and Emery, 2006)

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=127mm in the original Dehlen (1962) curvature meter and 200mm 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

4. EXISTING DEFLECTION BOWL PARAMETER CORRELATIONS

BLI, MLI and LLI have been found to have good correlations with flexible pavement structural conditions of respectively zones 1, 2 and 3 of such flexible pavement layers in South Africa (Horak, 1988). The use of these deflection bowl parameters in the evaluation of the structural capacity of a flexible pavement were developed and used by several researchers to aid the structural evaluation of South African flexible pavement structures (Maree and Bellekens, 1991 and Maree and Jooste, 1999). Basic correlations and tolerances for these deflection bowl parameters are included in TRH12 (CSRA, 1997) dealing with 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 40kN load (566kPa contact pressure) of a selection of representative typical South African flexible pavement structures (granular, bituminous and cemented base pavements). Elastic moduli were determined

Met opmaak: Engels (Groot-Brittannië) by means of back-analysis procedures with the known layer thicknesses. These pavement structures were analysed mechanistically, 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 80kN axle repetitions (E80s)) determined. These correlations were developed for various pavement types (granular, cemented and asphalt bases) and is quite useful in pavement response analysis. (Maree and Jooste, 1999 and Horak and Emery, 2006). These correlations as established thus for these deflection bowl parameters are shown in Figure 2.

However, using these correlations to determine remaining lives as a structural analysis in rehabilitation design and analysis of flexible pavements can lead to over simplification of a complex structural response with embarrassing inaccuracies. A more basic or fundamental level of application is advocated by steering away from remaining life calculations. The condition and behaviour state of pavement layers are good indicators of structural integritty (Horak and Emery, 2006). These correlations developed by Maree, Belleken and Jooste should rather be converted to these behaviour states and used as a benchmarking approach. It therefore compares the behaviour state of the pavement structure which changes over the life cycle of the pavement.

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The concept of behaviour states of pavements, described by Freeme (1983), originally made use of maximum deflection to classify pavement structural condition in terms of elastic response. This behaviour state classification was subsequently expanded by Horak (1988) to include the other deflection bowl parameters which gave better representation of the whole deflection bowl. In Table 2 such an example of behaviour state classification for granular pavements is shown as included in TRH12 (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. Experience with pavement rehabilitation analyses have found that these basic classes or behaviour states classification are already useful in a first level pavement structural response of the pavement as a whole.

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

Behaviour state	Traffic range (E80s millions)	Max Deflection (mm)	BLI (mm)	MLI (mm)	LLI (mm)
Very stiff	12 to 50	<0.30	<0.08	<0.05	<0.04
Stiff	3 to 8	0.30 to 0.50	0.08 to 0.25	0.05 to 0.15	0.04 to 0.08
Flexible	0.8 to 3	0.50 to 0.75	0.25 to 0.50	0.15 to 0.20	0.08 to 0.10
Very flexible	< 0.8	>0.75	>0.50	>0.20	>0.10

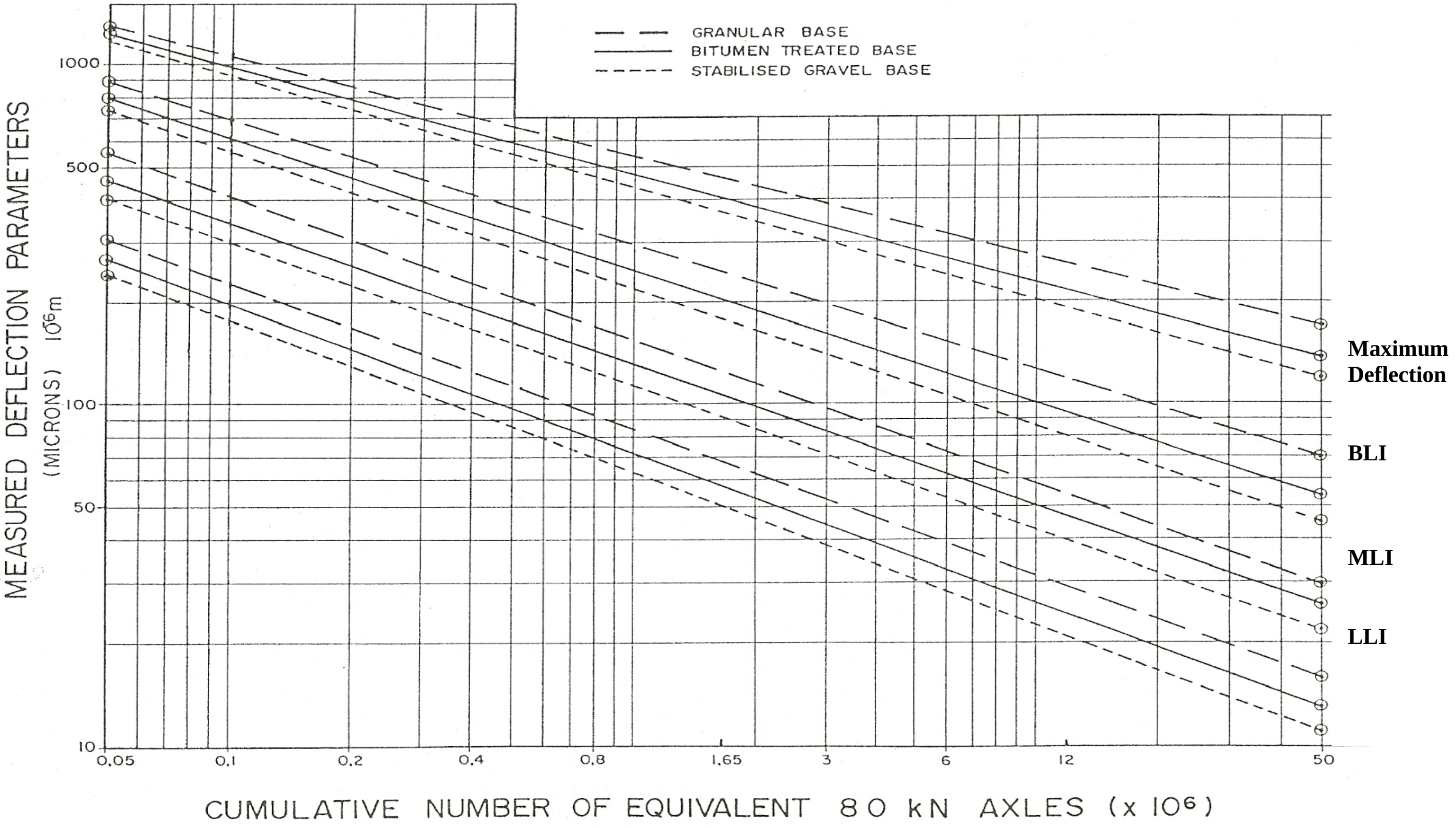

Figure 2. Correlation between deflection bowl parameters and remaining life

5. BENCHMARKING WITH DEFLECTION BOWL PARAMETERS

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Experience with condition rating of flexible pavements in SA has shown that visual condition rating can be linked with such behaviour states and help explain or direct and guide 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 summarized in a simple three tiered condition rating description. Such visual condition survey ratings allow the pavement to be summarized and presented graphically over length of the pavement with this three tiered colour coding condition rating expressed as , sound, warning or severe. This is often referred to as the RAG system (Red, Amber and Green). The use of colour provides a simple yet effective graphical summary presentation over the length of a pavement enabling relative benchmarking of conditions of pavement sections and helps to steer further detail 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 pavement layer thickness, etc is needed for such a relative benchmarking as the correlations developed by Maree and Bellekens (1991) and Maree and Jooste (1999) and the behaviour states described in Table 2 are used as basis for the development of such a relative structural benchmarking. In essence it means that the four tiered classification of the behaviour states of Table 3 is converted to a three tiered system by leaving the very stiff pavements out as they would normally be structurally sound and not be of primary concern in a rehabilitation analysis. The colour coding and rating system normally used in graphical plots are also indicated, namely sound, warning or severe. In Table 3 such a benchmarking classification for various flexible road pavement types is illustrated as developed over time. These benchmark criteria are based on a FWD contact drop contact stress of 566kPa (40kN drop weight) and roughly for a remaining life situation of 0.3 million E80 repetitions as shown in Figure 2.

Table 3: Deflection bowl parameter structural condition rating criteria for various road 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

These ranges of the benchmark values can thus be changed for various traffic situations, but experience have shown that these ranges provide very good results. This is ultimately a relative or comparative method of structural analysis and by using such a setting consistently provides broader and consistent comparison.

Relative or benchmarked structural deficiencies of the related structural layers in the pavement structure can be identified over the length of road and have been found to correlate very well with the visual survey information as manifested in terms of various distress phenomena. 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 thus be established at an early stage of the investigation with limited complicated analyses.

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5. ADJUSTING BENCHMARKING CRITERIA FOR AIRCRAFT LOADING

Often the Heavy Falling Weight Deflectometer (HWD) (Ricald, 2007) is used in the analysis of airport pavement structures. However, the FWD is more widely available and can test many pavement structures over a range of loading conditions with reasonable results, except for the heaviest pavements under great loading which demands the use of the HWD. The FWD loading can range from 566kPa (correlates with 40kN drop weight) to 1700kPa (correlates with 120kN drop weight). The 1415 kPa contact stress is in the ballpark for the contact stress under a Boeing 747-400, although the depth of influence is less than an HWD. The latter aircraft is often used as the design aircraft in airport pavement analyses. There are two methods found which can give realistic benchmark ranges for the selected deflection bowl parameters for aircraft pavements.

The first approach is based on a generic correlation between aircraft loading and normal 80kN axle loading. Experience has been built up in structural analyses in South Africa on various airport flexible pavement structures using various software linked to mechanistic based analyses procedures (e.g. ELMOD) as well as the more empirical analyses procedures (older FAA procedures) which have been crosschecked with the software normally used in SA on roads (e.g. MePADs software of the CSIR). Through experience, a general rough conversion factor was established for approximately 1 000 E80 repetitions or equivalent single axle loads (ESALs) being equal to one B747-400 pass as a ball park and benchmark factor.

This approach is used mostly in airport flexible pavement analyses which have relatively low volume of design aircraft passes, of which there are many. It is not suited to the high volume heavily trafficked aircraft pavements which will require more advanced analysis even at the first pass stage. It is intended for airports with granular basecourses, as opposed to cement stabilised or asphalt basecourses; such airports are common in medium sized airports in South Africa and Australia. A relative or benchmark methodology for these low volume airports was possible by adjusting the benchmark criteria for the road situation (566kPa) to that of an airport (1415kPa) for a typical range of 3 000 remaining life passes of a Boeing 747-400. This conversion of criteria from road pavements to airport flexible pavements for a granular base are as illustrated in Table 4 to follow. This was therefore also established from Figure 2 for this lower equivalent E80 range of repetitions.

The second method is to assume linear elasticity for the range of contact stress versus deflection bowl parameter ranges. By using the values shown in Table 3 as basis a new range of values can be deduced as illustrated in Table 5 for a granular base pavement type for the 1700kPa contact stress situation. These values had obviously been rounded off to help simplify the analysis procedure which is largely graphical in nature and which shows that there is enough room for further adjustments once the concept is understood that this is merely a comparative benchmark and should not be confused with actual structural strength of the pavement structure or its layers. This also leaves enough freedom to develop specific benchmark criteria for specific design aircraft based on their different contact stress figures.

Table 4. Benchmark ranges for 1415kPa contact stress on a granular base airport pavement

Structural condition rating	Deflection bowl parameter ranges			
	Max deflection (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1875	<1125	<625	<375
Warning	1875-2500	1125-1320	625-1000	375-625
Severe	>2500	>1320	>1000	>625

Table 5. Benchmark ranges for 1700kPa contact stress on a granular base airport pavement

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Structural condition rating	Deflection bowl parameter ranges			
	Max deflection (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1500	<600	<300	<180
Warning	1500 to 2500	600 to 1500	300 to 600	180 to 300
Severe	>2500	>1500	>600	>305

6. ILLUSTRATION OF BENCHMARK METHOD ON AIRPORT PAVEMENTS.

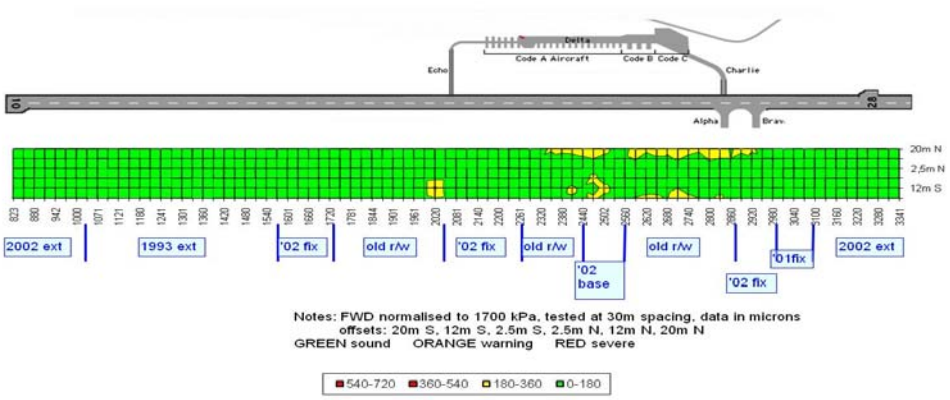
Broome International Airport in Australia was recently surveyed with a FWD in order to verify structural improvements by means of special maintenance activities as well as identify areas in need of additional rehabilitation and special maintenance activities. This is a low traffic volume airport with infrequent Boeing 737 and occasional Boeing 767 aircraft. Since the FWD survey can be done on a grid pattern over the full width and length of the runway pavement it is possible to develop isographs for each of the deflection bowl parameters.

The use of BLI, MLI and LLI enabled a much more comprehensive understanding of the pavement and its performance. In Figure 3a the LLI isograph is shown which relates to the subgrade structural condition. It clearly identifies the areas on the runway shoulders which happen to coincide with visual observation of distress in those areas. In Figure 3b the MLI isograph shows that the subgrade areas clearly contribute to less support in the subbase region of the pavement structure in these shoulder areas on the left hand side leading to the identification of severe areas of structural strength condition also in the sub base zone of the pavement structure.

In spite of some rehabilitation and strengthening of the base layer in these areas the BLI isograph in Figure 3c shows that the lack of support from the lower layers indicate that the base and surfacing is also in trouble in the red areas. The other areas thus indicated in the base and surfacing were also confirmed by visual signs of distress and subsequent repairs confirmed that the distress was confined to the base and surfacing layers only.

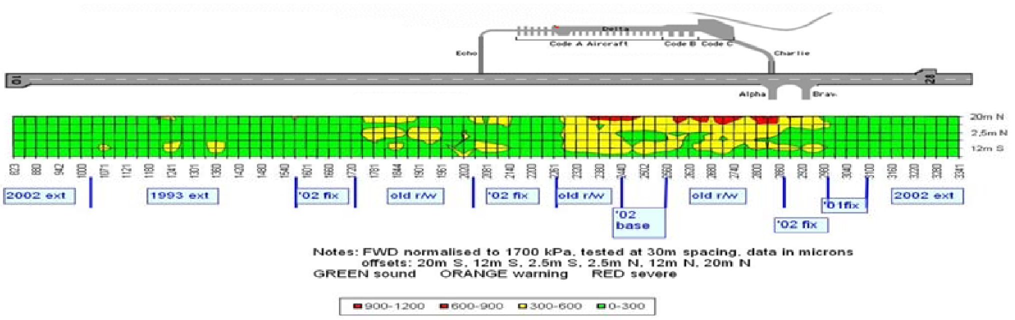
Eros airport in Windhoek, Namibia, is currently also under rehabilitation investigation. The results of a FWD survey were processed into the isograph format of the LLI, MLI and BLI as shown in Figure 4 to follow. It clearly shows that the visual survey results (not shown here for the sake of brevity) where extensive cracking and undulations occur, are due to the base and surfacing layer being the structurally deficient layer. The sub base and subgrade areas are comparatively strong. Additional test pit and dynamic cone penetrometer (DCP) results confirm this observation. In this case the structural strengthening needed is clearly directed at improving the base and surfacing layer.

Figure 3a **Broome 10/28 : LLI 2008 lower layer index**



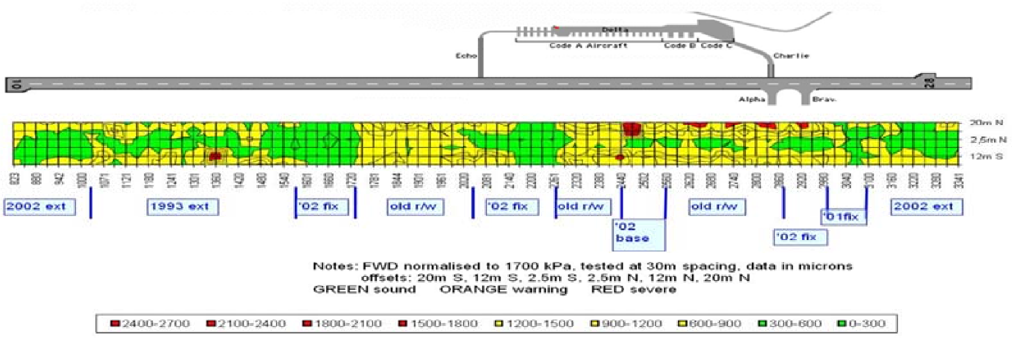
Notes: FWD normalised to 1700 kPa, tested at 30m spacing, data in microns
offsets: 20m S, 12m S, 2.5m S, 2.5m N, 12m N, 20m N
GREEN sound ORANGE warning RED severe

Figure 3b **Broome 10/28 : MLI 2008 middle layer index**



Notes: FWD normalised to 1700 kPa, tested at 30m spacing, data in microns
offsets: 20m S, 12m S, 2.5m S, 2.5m N, 12m N, 20m N
GREEN sound ORANGE warning RED severe

Figure 3c **Broome 10/28 : BLI 2008 base layer index**



Notes: FWD normalised to 1700 kPa, tested at 30m spacing, data in microns
offsets: 20m S, 12m S, 2.5m S, 2.5m N, 12m N, 20m N
GREEN sound ORANGE warning RED severe

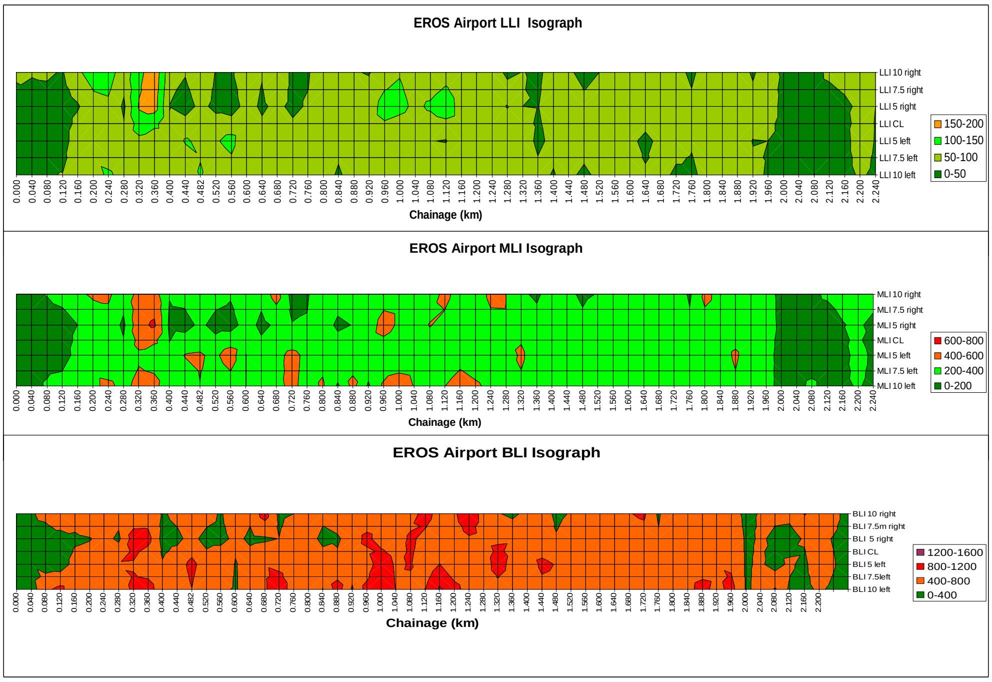


Figure 4. Deflection bowl isographs of Eros airport, Namibia.

7. CONCLUSION

Deflection bowl parameters describing three zones of the classical form of the deflection bowl have shown to correlate very well with the structural condition state of the base and surfacing zone, the sub base zone and the subgrade and selected layer zones of a granular basecourse, flexible pavement structure. Accelerated pavement testing (APT) and associated measurement technology have helped to develop correlations for the Base Layer Index (BLI), The Middle Layer Index (MLI) and the Lower Layer Index (LLI).

The same three tiered colour system of classification used with visual surveys in SA have been adapted to provide ranges for the sound, warning and severe conditions for the BLI, MLI and LLI indices. By using measured FWD deflection bowls these indices can be calculated with a simple spreadsheet. Graphical presentation as line graphs or isographs are very powerful tools to help isolate areas and zones on depth of the pavement where inadequate relative structural strength occurs. It has been shown how these criteria developed for roads evaluation were adapted for low volume airfield structural evaluation by using linear elastic response under different contact stress situations. In this way pavement layers with relatively weaker structural strength can be identified on the surface as well as depth of the pavement and help direct further detailed analyses cost effectively.

This FWD deflection bowl parameter benchmarking criteria developed for flexible road pavement analysis were adapted for granular basecourse aircraft loading situations. It had been used, as in the case with road pavements, on airport pavement rehabilitation investigations and found to be very helpful. A few examples of such application in rehabilitation investigations were given.

However, this benchmark method should only be used as a first phase or level of investigation in pavement rehabilitation analyses. It helps to identify areas and layers which are in relative distress or soundness without doing sophisticated mechanistic type analyses. It can help to guide and steer the next level of more detailed and more expensive analyses and investigations correctly to the areas where it is needed in a cost effective and efficient manner.

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