Using Falling Weight Deflectometer Readings to Conduct Structural Benchmarking of Airport Pavement Structures

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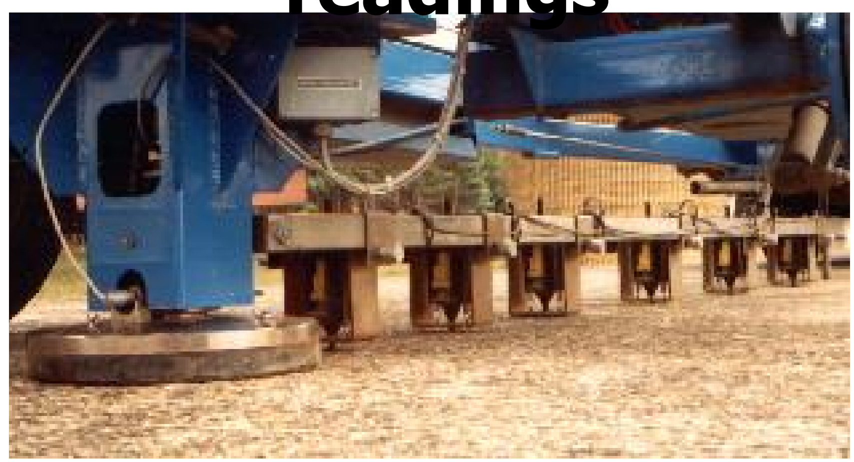
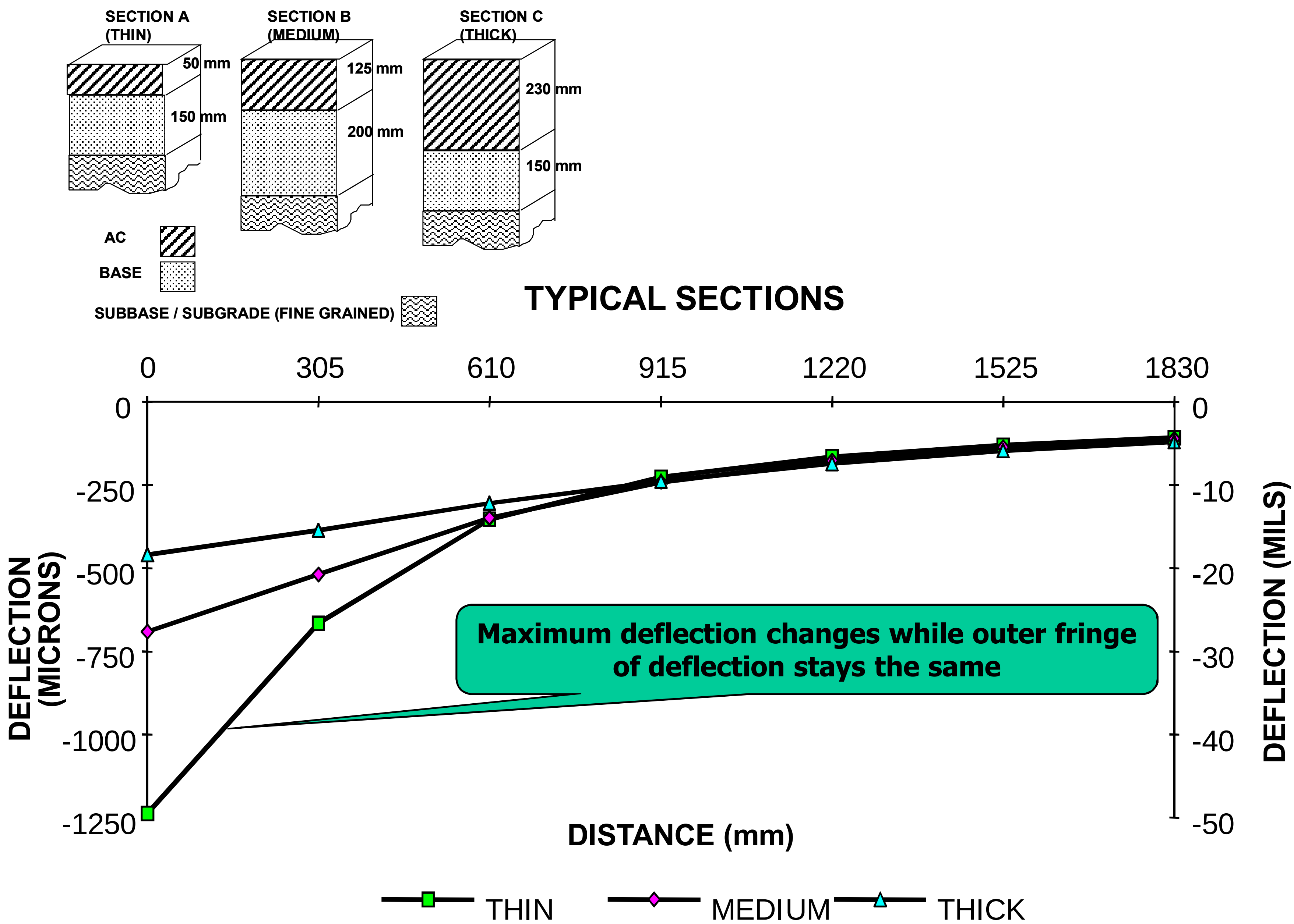
Non-destructive simplified mechanistic/empirical structural evaluation demonstrated with various airports

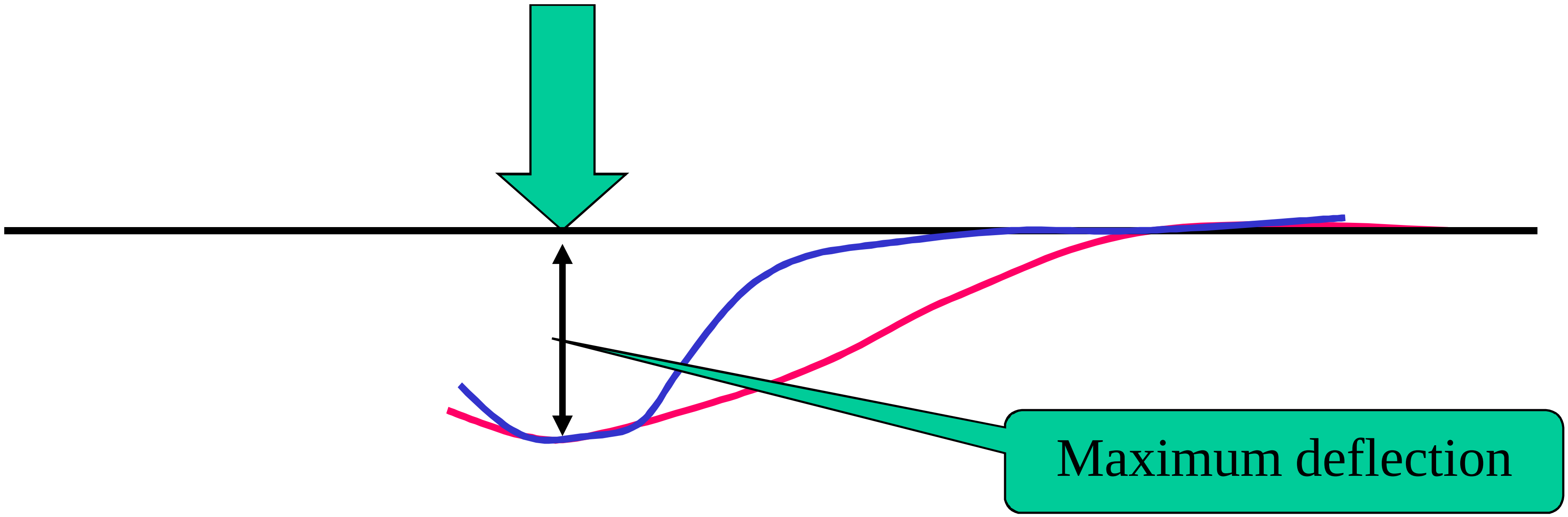
The automated FWD is a vast improvement over the old manual method of reading Benkelman Beam readings

The Benkelman Beam used the rebound method of measuring deflection and various empirical relationships were developed





SECTION A
(THIN)
50 mm
150 mm
SECTION B
(MEDIUM)
125 mm
200 mm
SECTION C
(THICK)
230 mm
150 mm
AC
BASE
SUBBASE / SUBGRADE (FINE GRAINED)
TYPICAL SECTIONS
0
305
610
915
1220
1525
1830
0
-250
-500
-750
-1000
-1250
DEFLECTION
(MICRONS)
0
-10
-20
-30
-40
-50
DEFLECTION (MILS)
Maximum deflection changes while outer fringe of deflection stays the same
DISTANCE (mm)
THIN
MEDIUM
THICK



Therefore even the same maximum deflection may be due to two different pavement systems

Typical collage of empirical design curves based on maximum deflection with low accuracy

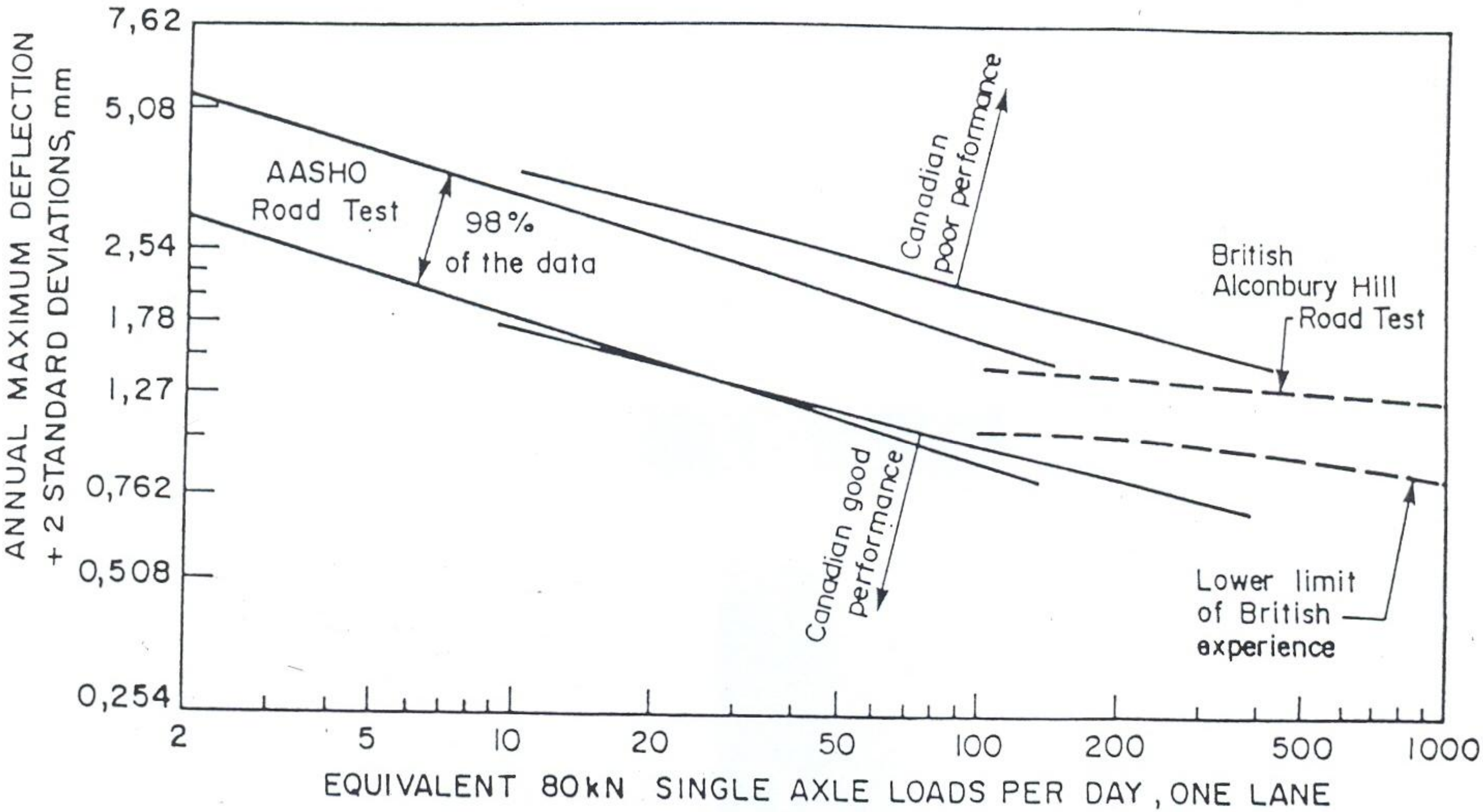
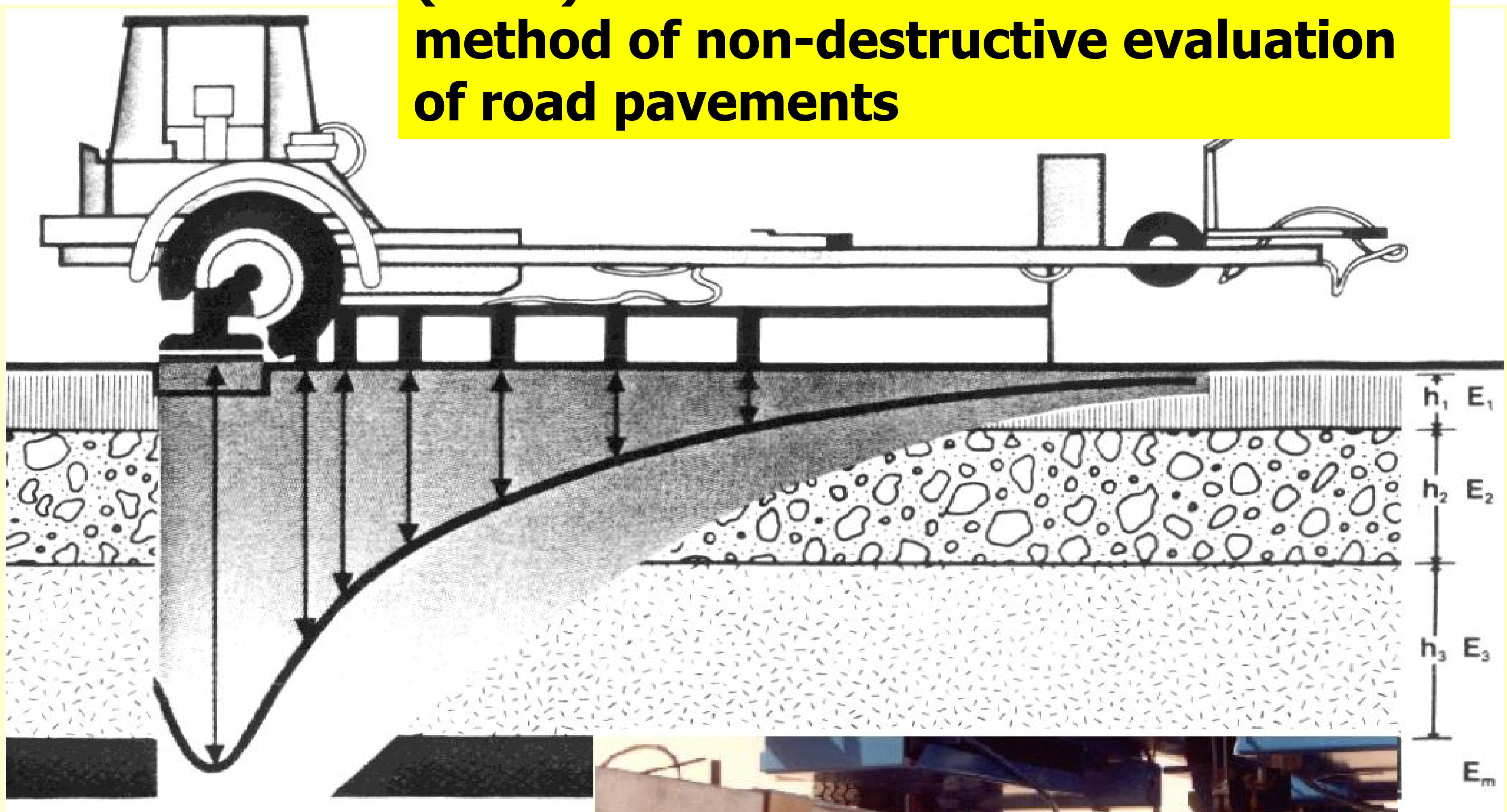


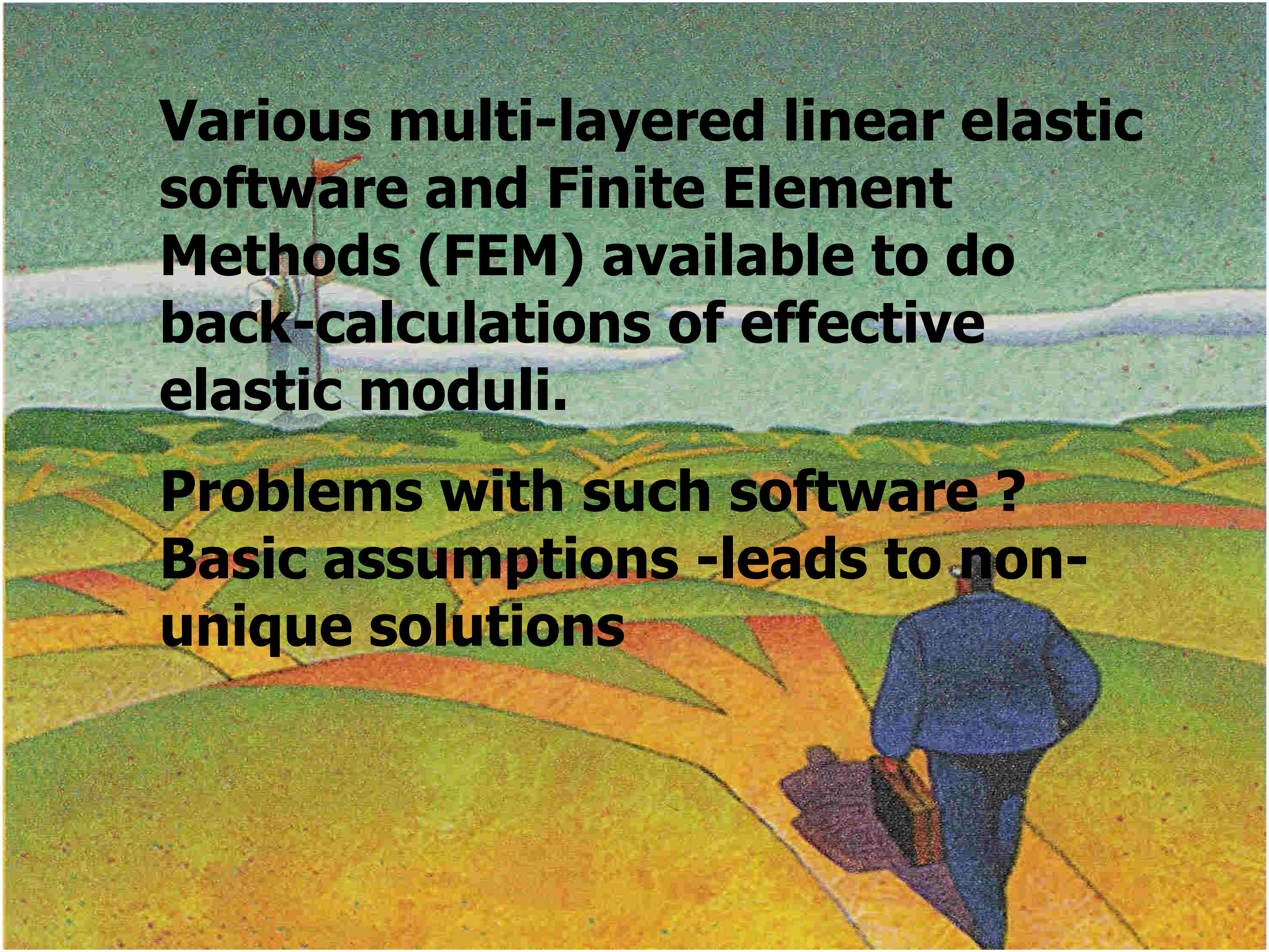
FIGURE 18

EXPERIENCE FROM ROAD TESTS AND CANADA (After Kingham[61])

The Falling Weight Deflectometer (FWD) has become the standard method of non-destructive evaluation of road pavements



Detail view of FWD geophones measuring deflection



Various multi-layered linear elastic software and Finite Element Methods (FEM) available to do back-calculations of effective elastic moduli.

Problems with such software ? Basic assumptions -leads to non-unique solutions

The Heavy duty FWD (HFWD) developed for airport pavement structure evaluations

L Ricalde 2007 FAA Worldwide Technology Transfer Conference, Atlantic City (HFWD benchmark method)

The ISM0, calculated using the maximum basin deflection (D0) under the load, is an indicator of the pavement condition itself.

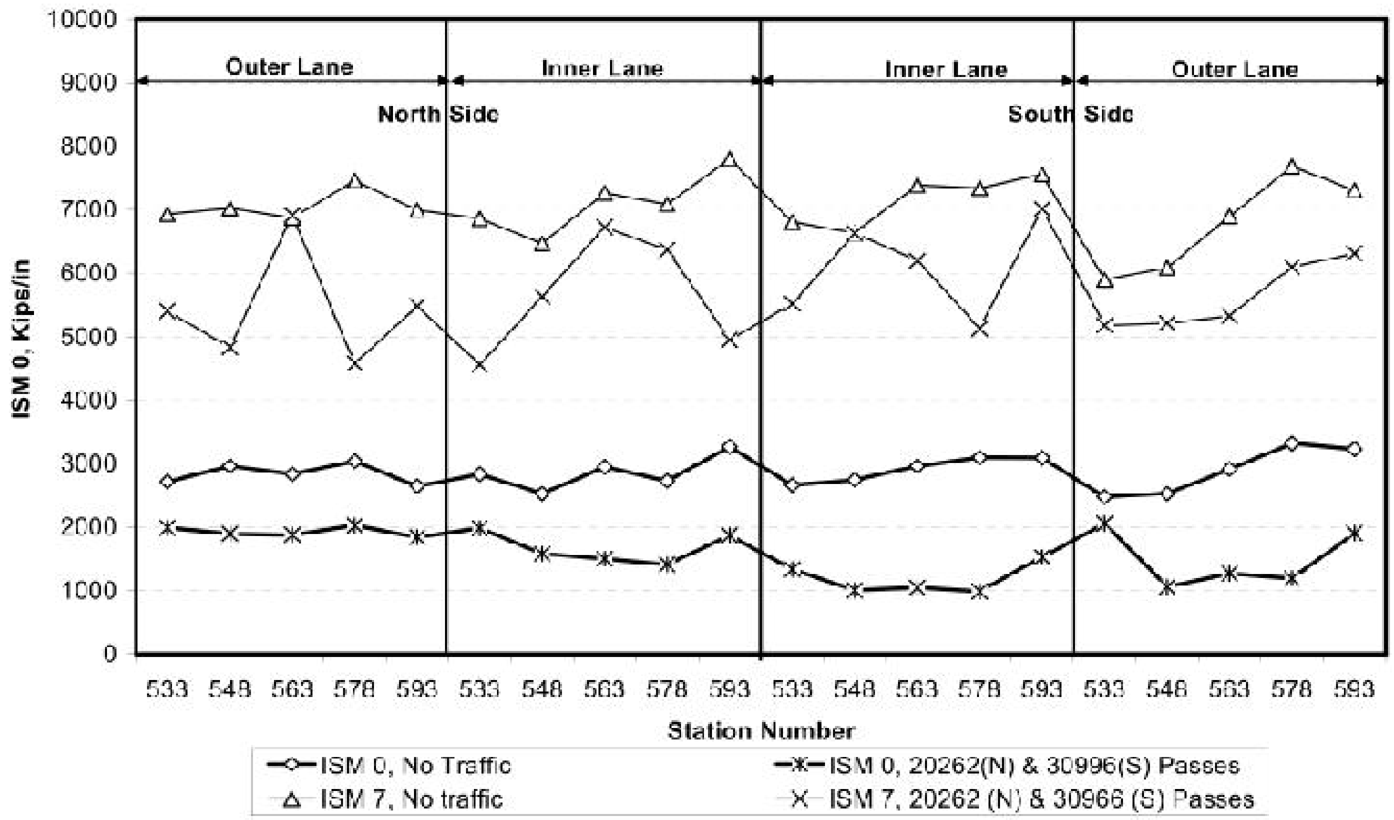
ISM0 = HWD Load/D0

Indication of total pavement response

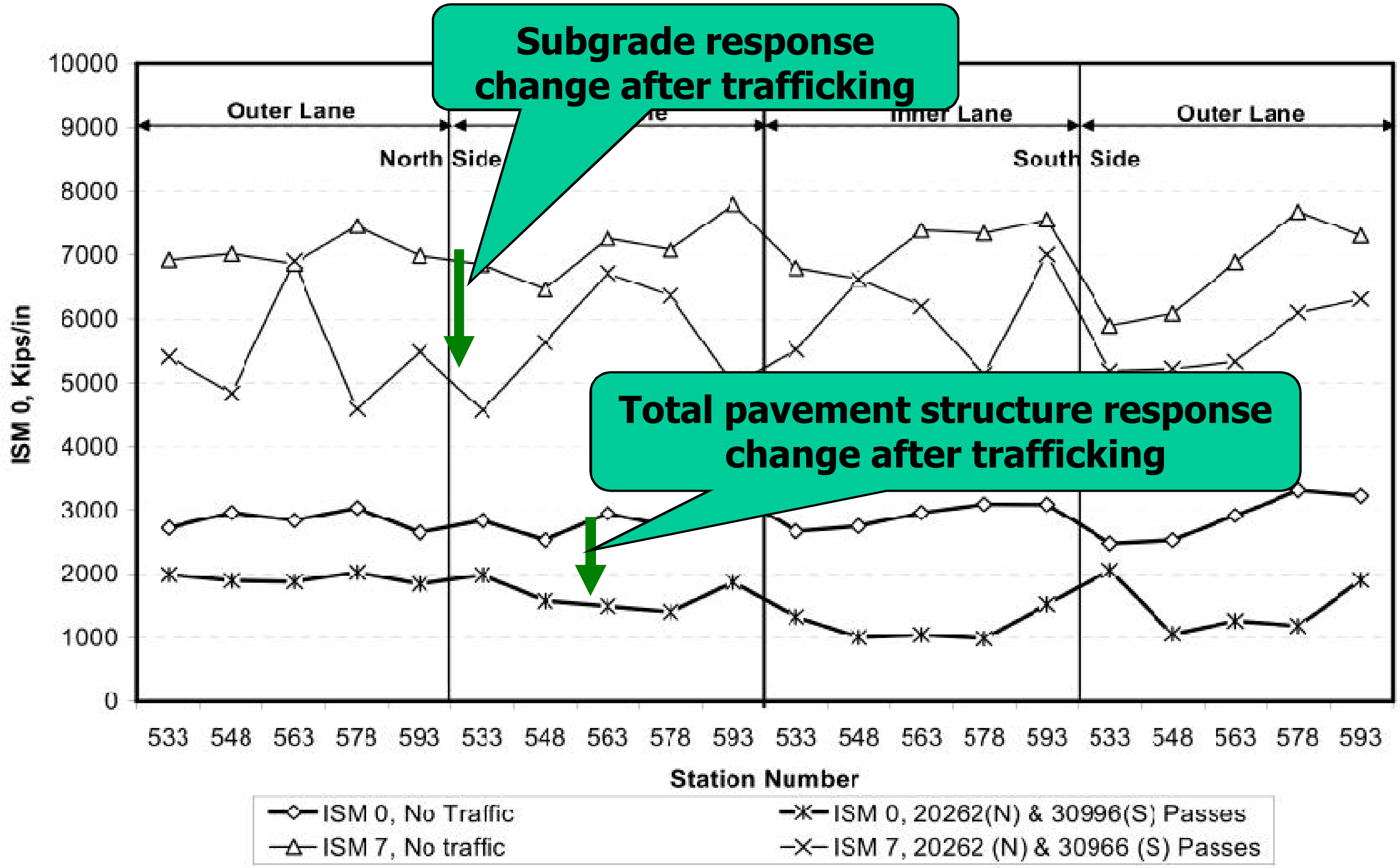
On the other hand ISM7, calculated using the deflection 72-in from the center load (D7), usually indicates the subgrade condition.

ISM7 = HWD Load/D7

Indication of subgrade response



ANALYSIS OF HWD DATA FROM CC2 TRAFFIC TESTS AT THE NATIONAL



L Ricalde, 2007, FAA Worldwide Technology Transfer Conferenec, Atlantic City

Accelerated pavement testing (APT) with the fleet of Heavy Vehicle Simulators (HVSs) in South Africa

- **Structural analysis, modeling & design of pavement systems**
- **APT, performance assessments, audits and material modeling**
- **Maintenance & pavement rehabilitation design methods**

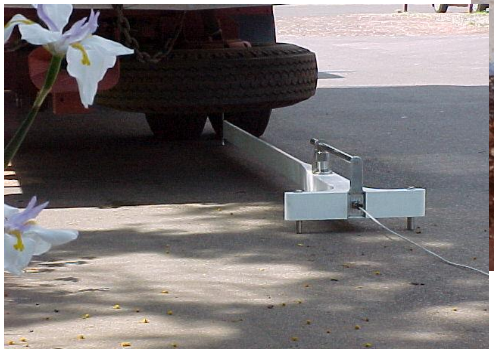


TABLE 3.1 : SUMMARY OF DEFLECTION Basin PARAMETERS (from Horak)

	PARAMETER	FORMULA	MEASURING DEVICE
1.	Maximum deflection	δ_0	Benkelman beam Lacroix deflectograph
2.	Radius of curvature	$R = \frac{r^2}{2\,\delta_0(\delta_0/\delta_r - 1)}$ r = 127 mm, 200 mm	Curvaturemeter, FWD with r = 127 mm and 200 mm respectively
3.	Spreadability	$\frac{[(\delta_0 + \delta_1 + \delta_2 + \delta_3)/5]100}{\delta_0}$ $\delta_1 \ldots \delta_3$ spaced 305 mm	Dynaflect, FWD
4.	Area	$A = 6[1 + 2(\delta_1/\delta_0) + 2^*(\delta_2/\delta_0) + \delta_3/\delta_0)]$	FWD
5.	Shape factors	$F_1 = (\delta_0 - \delta_2)/\delta_1$ $F_2 = (\delta_1 - \delta_3)/\delta_2$	FWD
6.	Base Layer Index, formerly Surface curvature index	$BLI = \delta_0 - \delta_r$, where $r = 305$ mm or $r = 500$ mm	Benkelman beam Road rater FWD
7.	Lower Layer Index, formerly Base curvature index	$LLI = \delta_{610} - \delta_{915}$	Road rater, FWD
8.	Middle Layer Index, formerly Base damage index	$MLI = \delta_{305} - \delta_{610}$	Road rater, FWD
9.	Deflection ratio	$Q_r = \delta_r/\delta_0$ where $\delta_r \approx \delta_0/2$	FWD
10.	Bending index	$BI = \delta\ /a$ where a = Deflection basin	Benkelman beam
11.	Slope of deflection	$SD = \tan^{-1}(\delta_0 - \delta_r)/r$ where r = 610 mm	Benkelman beam

δ_0 = center deflection (r = 0), δ_1, δ_2, δ_3 = first, second, third sensor from the load respectively, δ_{305} = deflection at 305 mm, etc.

Various deflection basin or bowl parameters can be calculated and used to evaluate the structural capacity of various aspects of the pavement structure.

Accelerated pavement testing (APT) with the HVS led to the development of the concept of states of behaviour of pavements

Freeme, Walker, Jordaan, Horak (1980s)

Behaviour state	Max Deflection
Very stiff	<0.3mm
Stiff	0.3 to 0.5
Flexible	0.5 to 0.75
Very flexible	>0.75

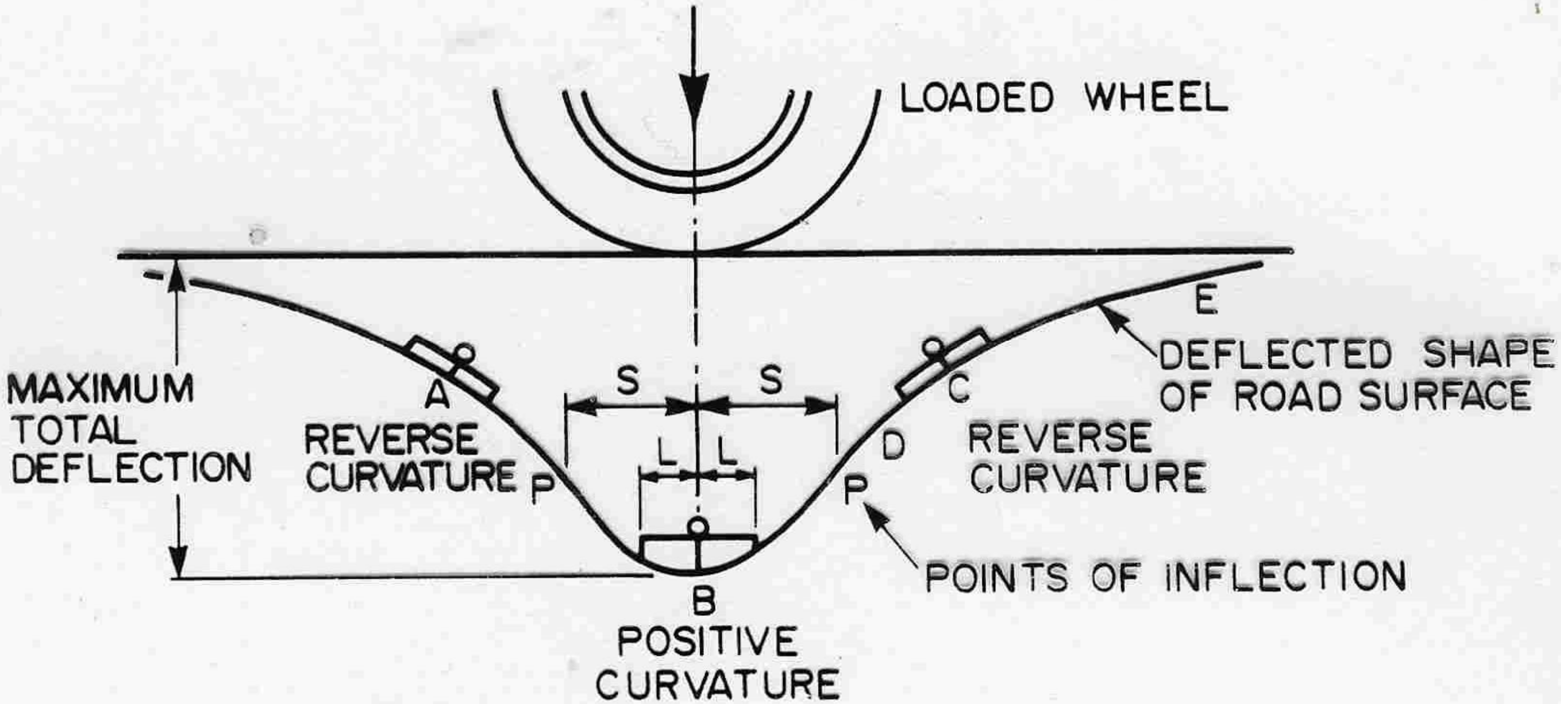
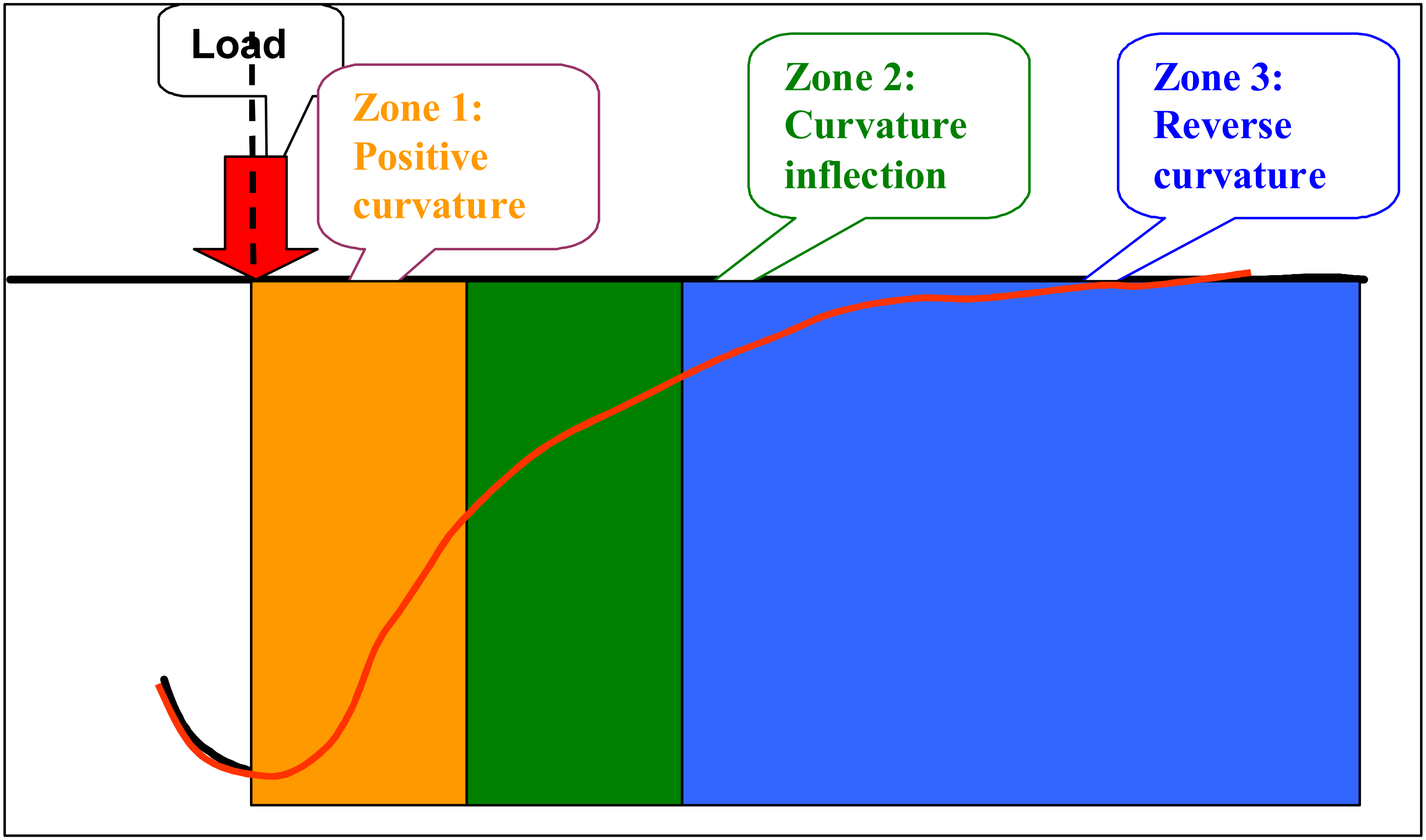
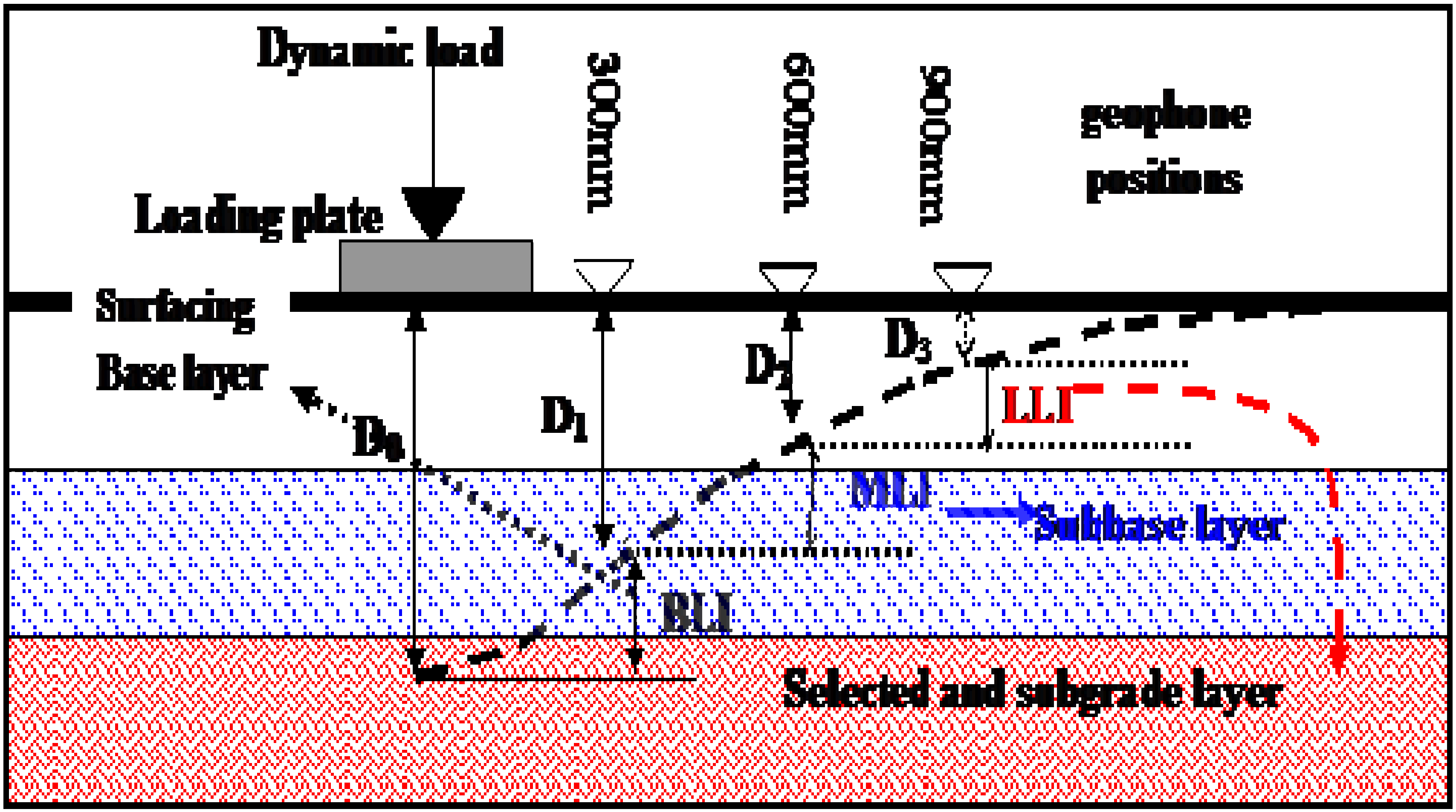


FIGURE 7

TYPICAL PATTERN OF DEFLECTION OF A ROAD SURFACE BENEATH A LOADED WHEEL


Load
Zone 1:
Positive
curvature
Zone 2:
Curvature
inflection
Zone 3:
Reverse
curvature

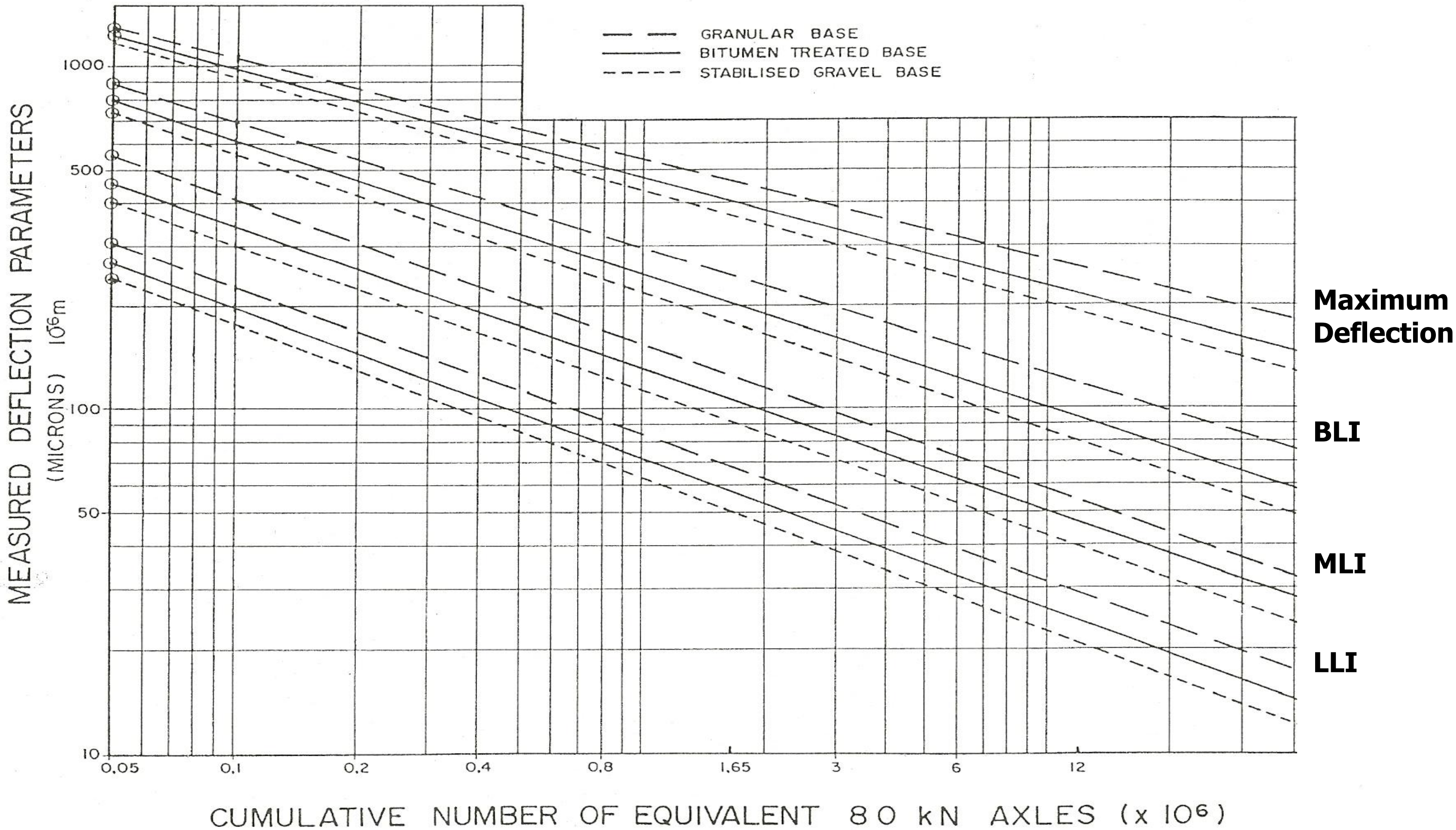
Deflection bowl parameters and correlation with structural layers



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)	$RoC = \frac{(L)^2}{2D_0(1-D_{200}/D_0)}$ Where L=127mm in the original Dehlen curvature meter and 200mm for the FWD	1
Base Layer Index (BLI)	$BLI=D_0-D_{300}$	1
Middle Layer Index (MLI)	$MLI=D_{300}-D_{600}$	2
Lower Layer Index (LLI)	$LLI=D_{600}-D_{900}$	3

Research done at CSIR on road pavements and backed by APT



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

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 the benchmarking

Benchmark criteria for a contact drop stress of 566kPa (40kN drop weight) for E80 traffic range of 0.3million (Maree and Jooste, RADC research document RP 91/325)

Structural Condition Rating	Deflection bowl parameter and ranges			
	Max. Defl (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<750	<450	< 250	<150
Warning	750 to 1000	450 to 600	250 to 400	150 to 250
Severe	>1000	> 600	> 400	> 205

Assumption: One B747-400 repetition is approximately 1000 ESALS

Proposed Benchmark criteria for a contact drop stress of 1415kPa (100kN drop weight) for 3 000 repetitions of a B747-400

Structural Condition Rating	Deflection bowl parameter and ranges			
	Max. Defl (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1875	<1125	< 625	<375
Warning	1875 to 2500	1125 to 1320	625 to 1000	375 to 625
Severe	>2500	> 1320	> 1000	> 625

Benchmark criteria for a contact drop stress of 1110kPa (80kN FWD drop weight)

Structural Condition Rating	Deflection bowl parameter and ranges			
	Max. Defl (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1000	<400	<200	<100
Warning	1000 to 1500	400 to 800	200 to 400	100 to 200
Severe	>1500	>800	>400	>200

Benchmark criteria for a contact drop stress of 1415kPa (100kN FWD drop weight)

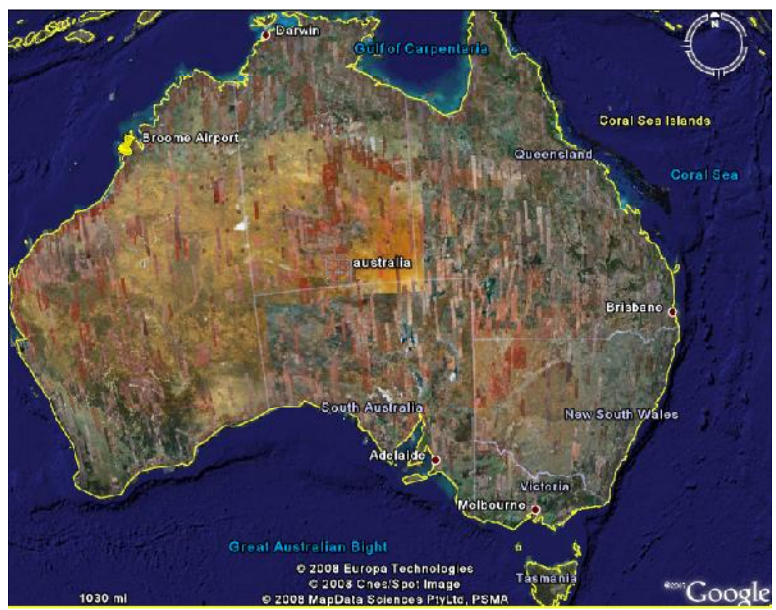
Structural Condition Rating	Deflection bowl parameter and ranges			
	Max. Defl (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1250	<500	<250	<125
Warning	1250 to 1875	500 to 1000	250 to 500	125 to 250
Severe	>1875	>1000	>500	>250

Benchmark criteria for a contact drop stress of 1700kPa (120kN FWD drop weight)

Structural Condition Rating	Deflection bowl parameter and ranges			
	Max. Defl (micrometer)	BLI (micrometer)	MLI (micrometer)	LLI (micrometer)
Sound	<1500	<600	<300	<180
Warn ing	1500 to 2500	600 to 1500	300 to 600	180 to 300
Severe	>2500	>1500	>600	>300

This is a relative or benchmark comparison: Therefore the limits can be adjusted to suit the specific situation


Broome Rd
Broome Domestic Airport
Broome


Darwin
Gulf of Carpentaria
Coral Sea Islands
Broome Airport
Queensland
Coral Sea
australia
Brisbane
South Australia
New South Wales
Adelaide
Victoria
Melbourne
Great Australian Bight
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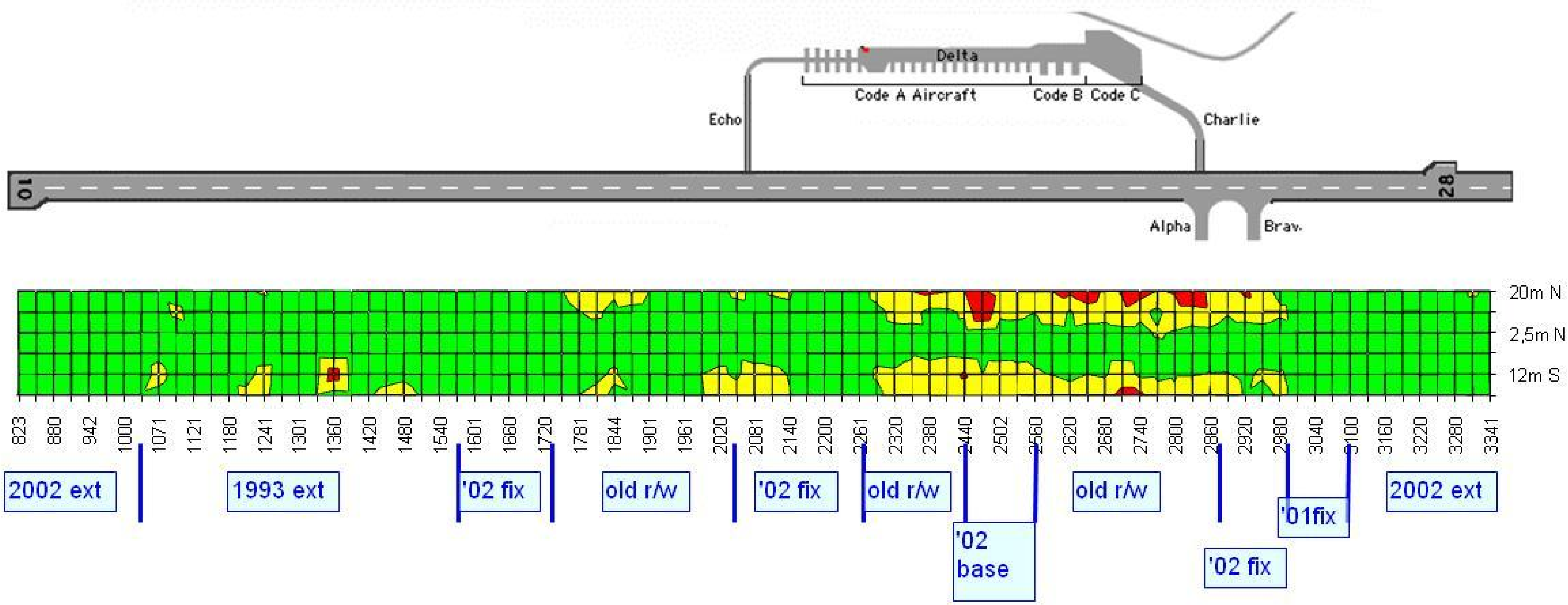
Tasmania
1030 mi
Google

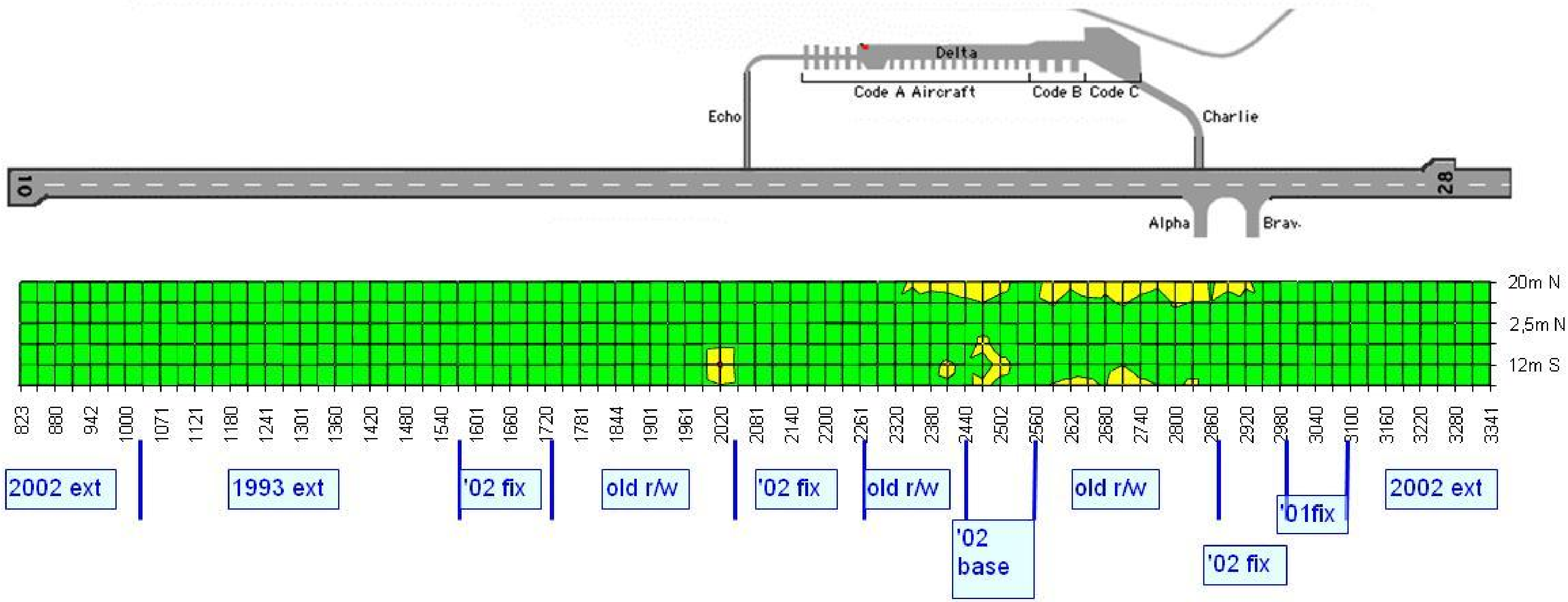
Broome 10/28 deflection 2008



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

3500-4500	2500-3500	1500-2500	500-1500

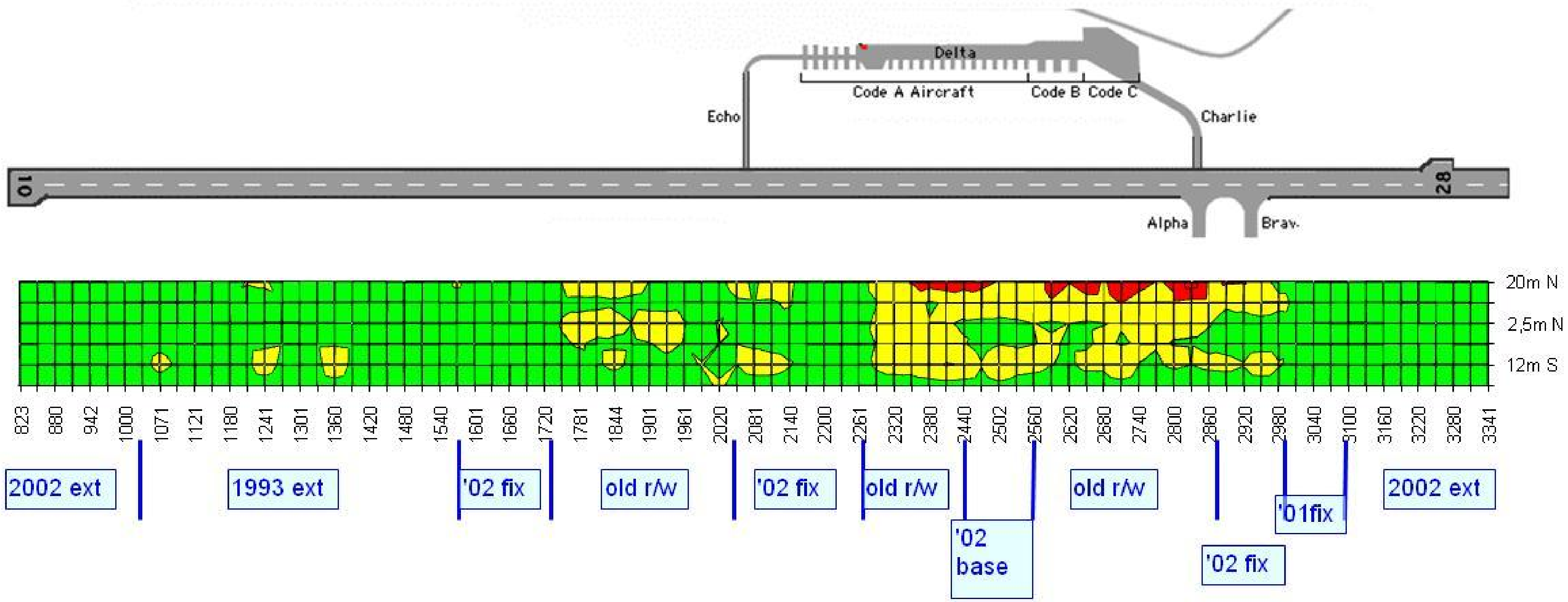
Broome 10/28 : LLI 2008 lower layer index



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

540-720 360-540 180-360 0-180

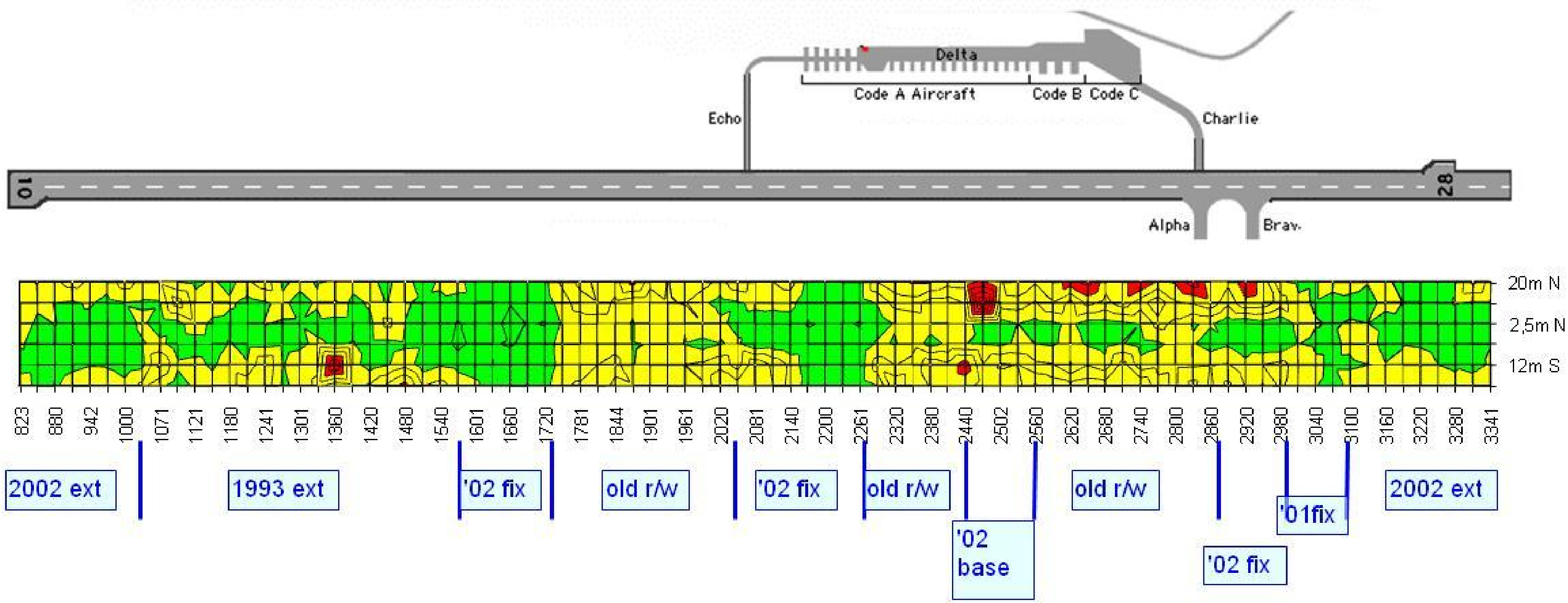
Broome 10/28 : MLI 2008 middle layer index



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

900-1200 600-900 300-600 0-300

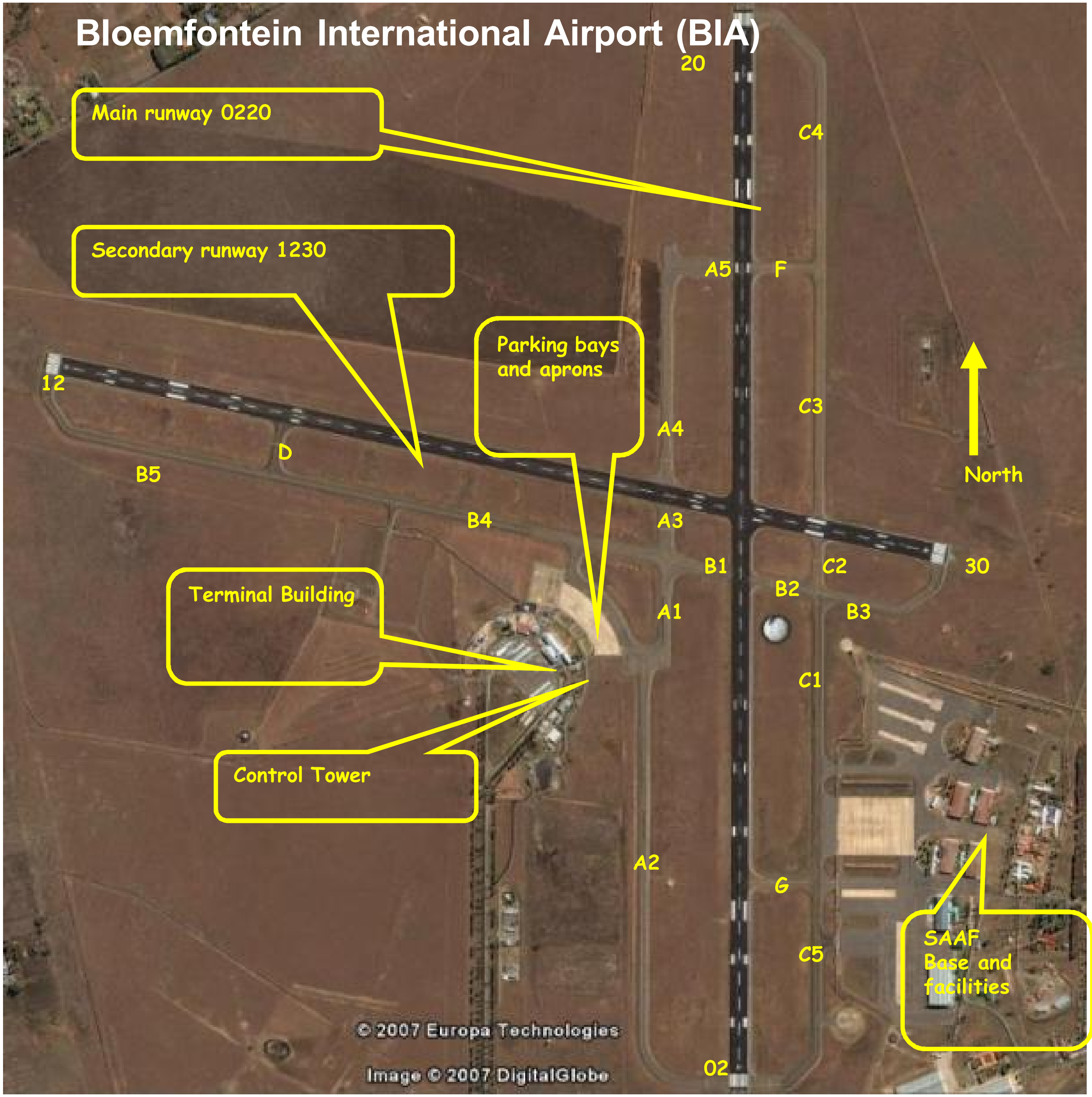
Broome 10/28 : BLI 2008 base layer index

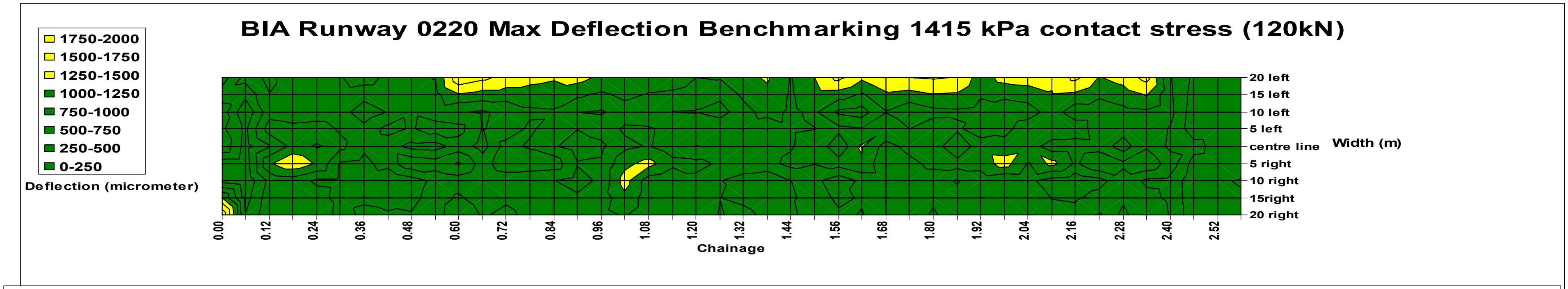


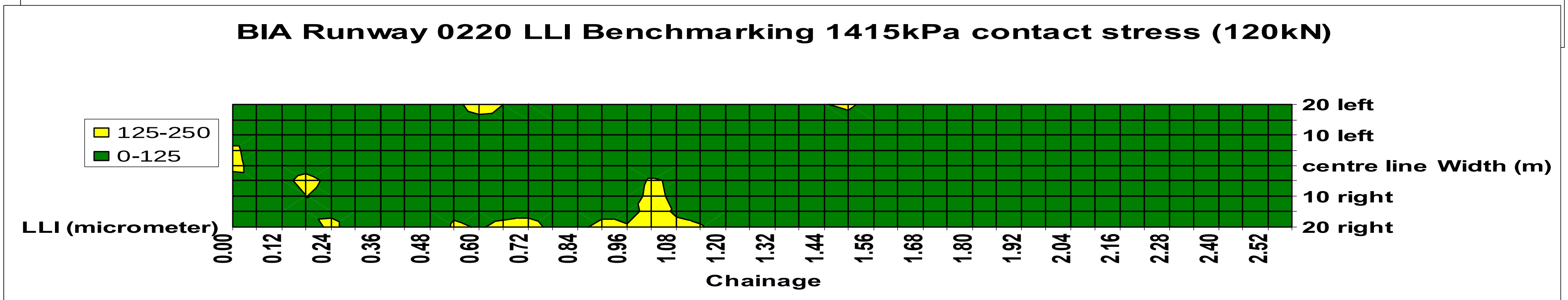
Notes: FWD normalised to 1700 kPa, tested at 30m spacing, data in microns
offsets: 20m S, 12m S, 2.5m S, 2.5m N, 12m N, 20m N
GREEN sound ORANGE warning RED severe

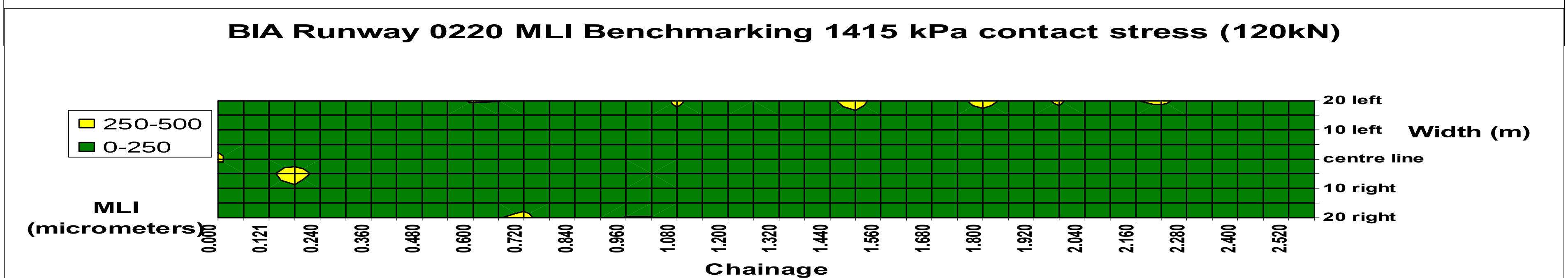
■2400-2700 ■2100-2400 ■1800-2100 ■1500-1800 ■1200-1500 ■900-1200 ■600-900 ■300-600 ■0-300

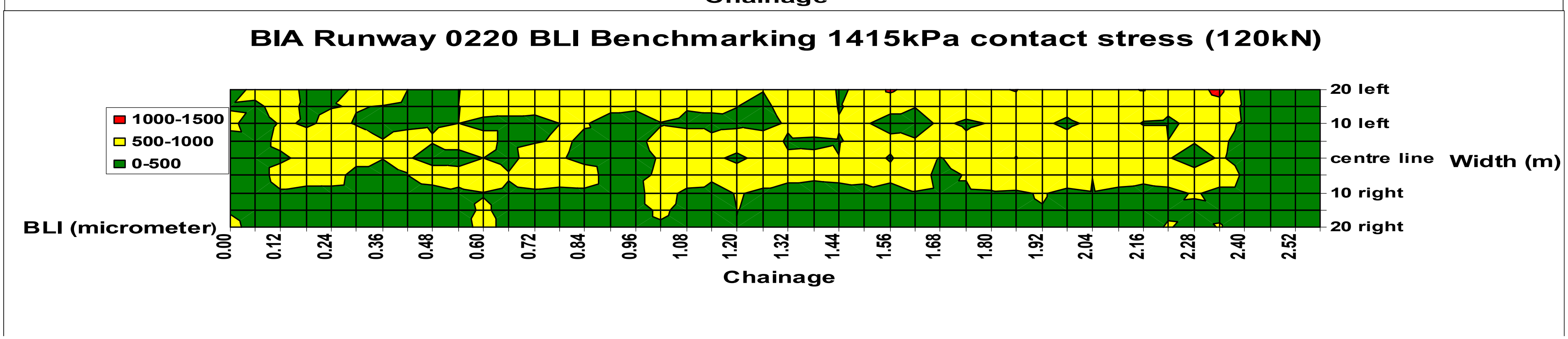
Rehabilitation and upgrade of runways and taxiways for 2010 World Cup Soccer

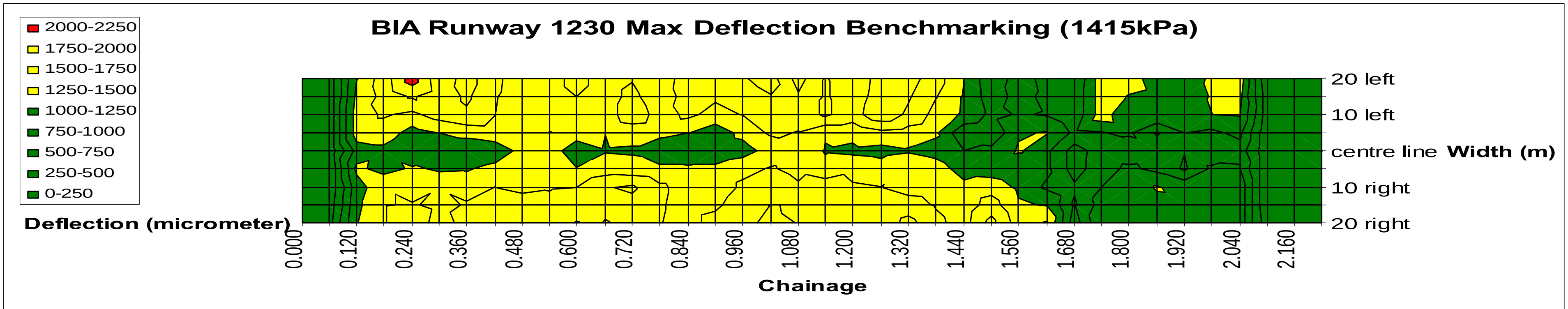


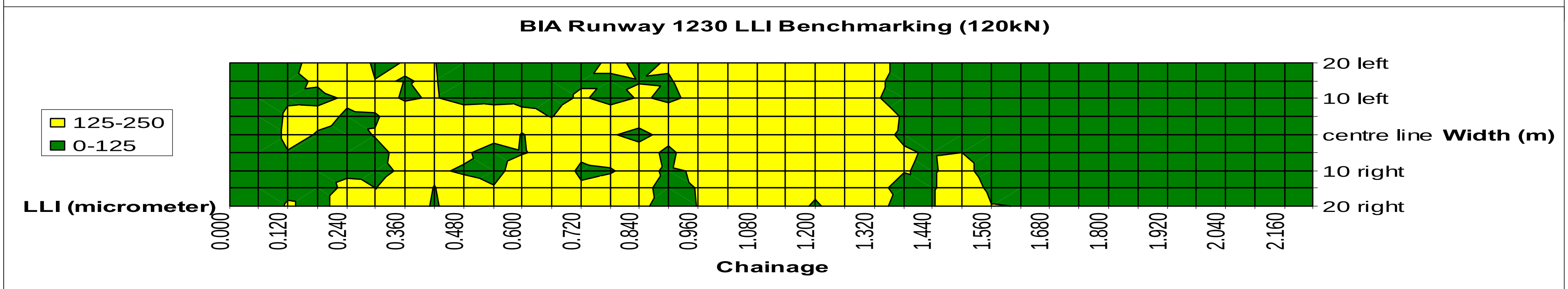

BIA Runway 0220 Max Deflection Benchmarking 1415 kPa contact stress (120kN)
1750-2000
1500-1750
1250-1500
1000-1250
750-1000
500-750
250-500
0-250
Deflection (micrometer)
20 left
15 left
10 left
5 left
centre line
5 right
10 right
15right
20 right
Width (m)
0.00 0.12 0.24 0.36 0.48 0.60 0.72 0.84 0.96 1.08 1.20 1.32 1.44 1.56 1.68 1.80 1.92 2.04 2.16 2.28 2.40 2.52
Chainage

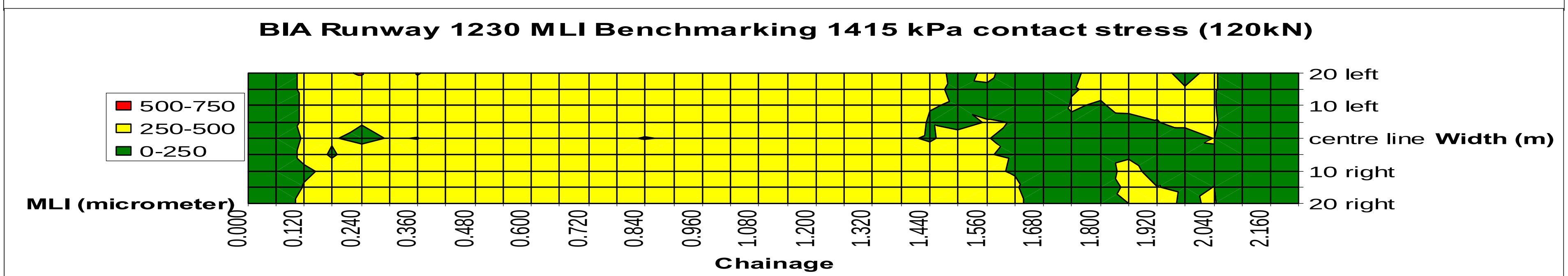

BIA Runway 0220 LLI Benchmarking 1415kPa contact stress (120kN)
125-250
0-125
LLI (micrometer)
20 left
10 left
centre line
10 right
20 right
Width (m)
0.00 0.12 0.24 0.36 0.48 0.60 0.72 0.84 0.96 1.08 1.20 1.32 1.44 1.56 1.68 1.80 1.92 2.04 2.16 2.28 2.40 2.52
Chainage

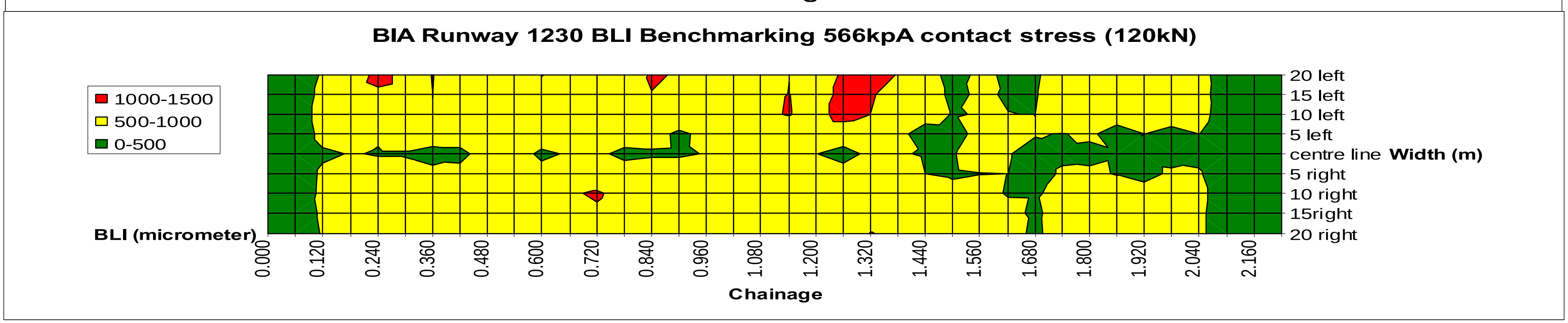

BIA Runway 0220 MLI Benchmarking 1415 kPa contact stress (120kN)
250-500
0-250
MLI (micrometers)
20 left
10 left
centre line
10 right
20 right
Width (m)
0.000 0.121 0.240 0.360 0.480 0.600 0.720 0.840 0.960 1.080 1.200 1.320 1.440 1.560 1.680 1.800 1.920 2.040 2.160 2.280 2.400 2.520
Chainage


BIA Runway 0220 BLI Benchmarking 1415kPa contact stress (120kN)
1000-1500
500-1000
0-500
BLI (micrometer)
20 left
10 left
centre line
10 right
20 right
Width (m)
0.00 0.12 0.24 0.36 0.48 0.60 0.72 0.84 0.96 1.08 1.20 1.32 1.44 1.56 1.68 1.80 1.92 2.04 2.16 2.28 2.40 2.52
Chainage

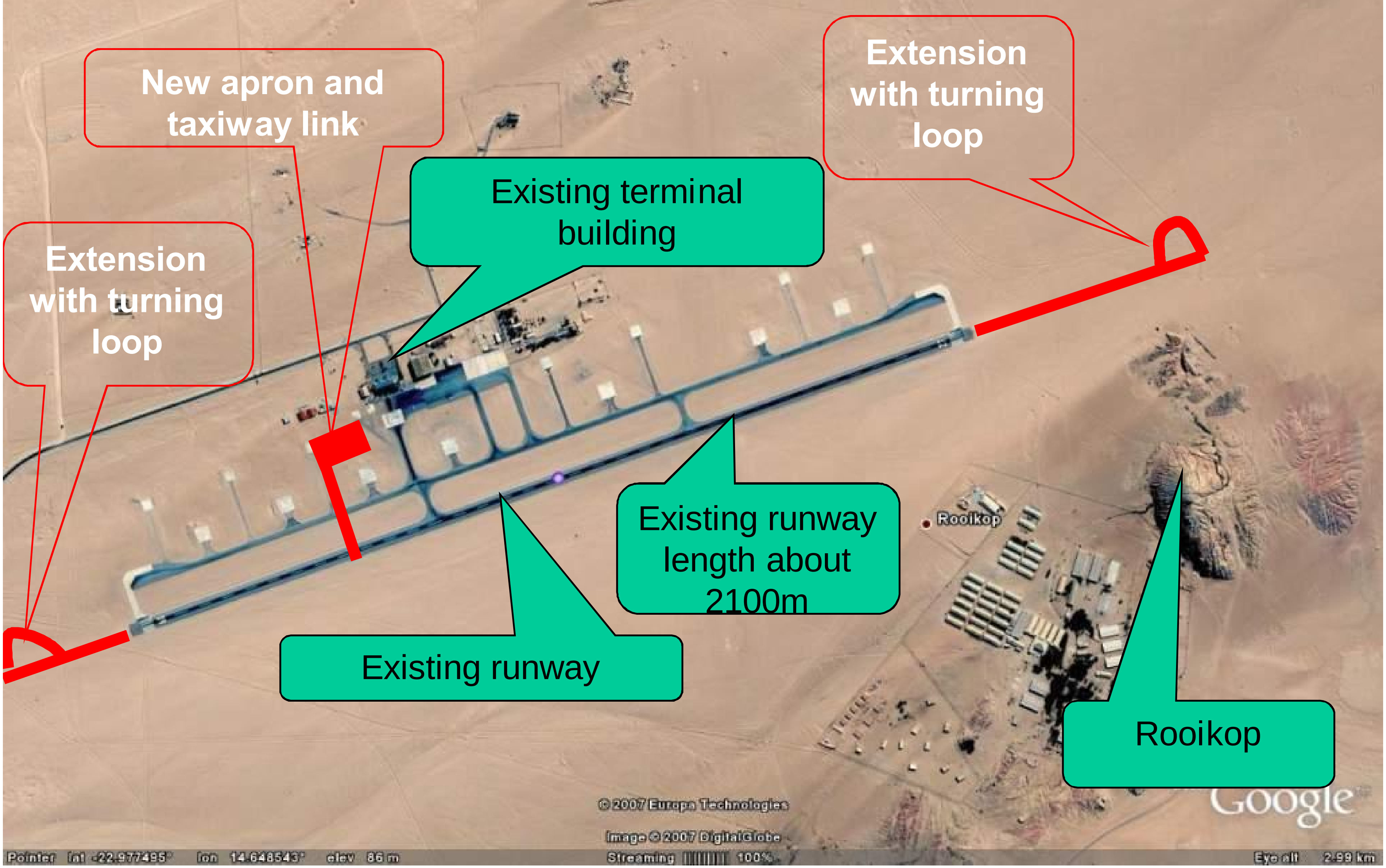

BIA Runway 1230 Max Deflection Benchmarking (1415kPa)
2000-2250
1750-2000
1500-1750
1250-1500
1000-1250
750-1000
500-750
250-500
0-250
Deflection (micrometer)
20 left
10 left
centre line Width (m)
10 right
20 right
0.000 0.120 0.240 0.360 0.480 0.600 0.720 0.840 0.960 1.080 1.200 1.320 1.440 1.560 1.680 1.800 1.920 2.040 2.160
Chainage


BIA Runway 1230 LLI Benchmarking (120kN)
125-250
0-125
LLI (micrometer)
20 left
10 left
centre line Width (m)
10 right
20 right
0.000 0.120 0.240 0.360 0.480 0.600 0.720 0.840 0.960 1.080 1.200 1.320 1.440 1.560 1.680 1.800 1.920 2.040 2.160
Chainage

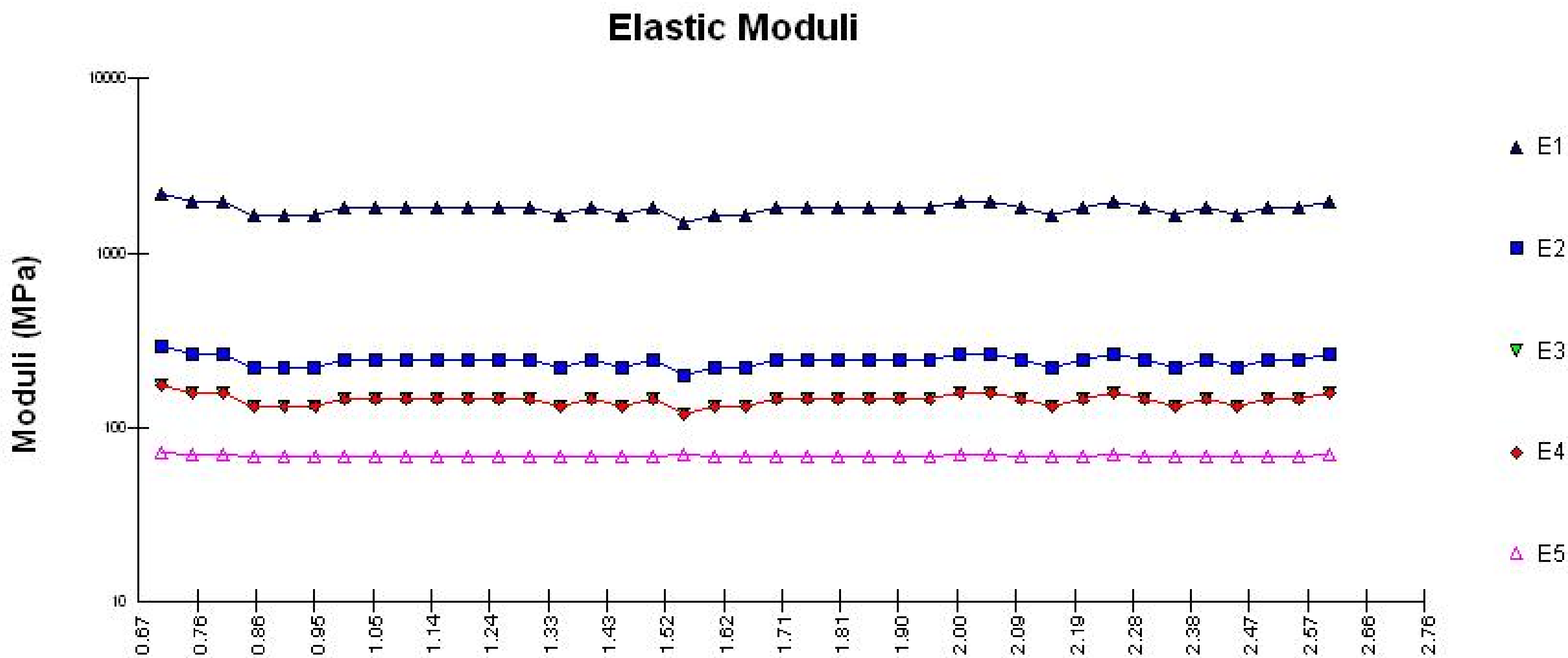

BIA Runway 1230 MLI Benchmarking 1415 kPa contact stress (120kN)
500-750
250-500
0-250
MLI (micrometer)
20 left
10 left
centre line Width (m)
10 right
20 right
0.000 0.120 0.240 0.360 0.480 0.600 0.720 0.840 0.960 1.080 1.200 1.320 1.440 1.560 1.680 1.800 1.920 2.040 2.160
Chainage


BIA Runway 1230 BLI Benchmarking 566kpA contact stress (120kN)
1000-1500
500-1000
0-500
BLI (micrometer)
20 left
15 left
10 left
5 left
centre line Width (m)
5 right
10 right
15right
20 right
0.000 0.120 0.240 0.360 0.480 0.600 0.720 0.840 0.960 1.080 1.200 1.320 1.440 1.560 1.680 1.800 1.920 2.040 2.160
Chainage

Involved with Walvisbay International Airport: Audit on upgrade to 4F classification and Design Alternatives

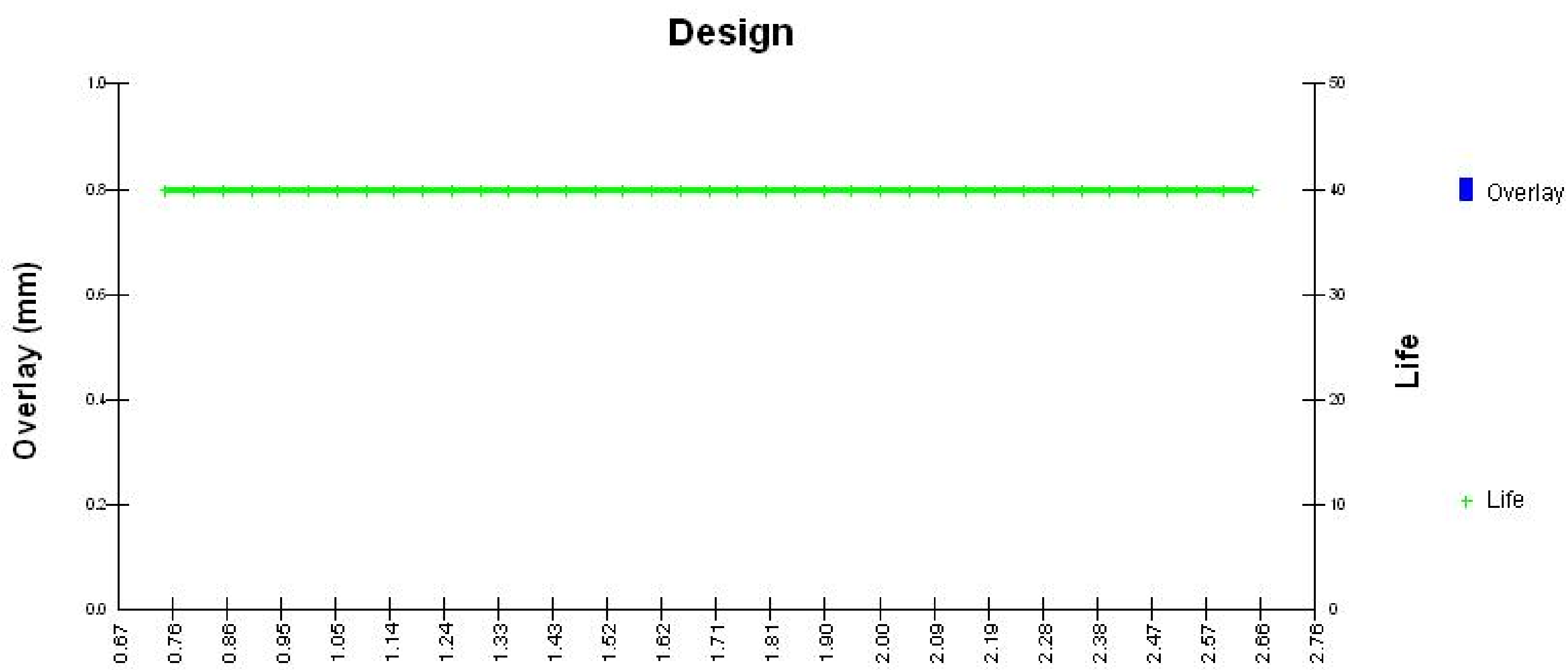


Effective elastic moduli back-calculated with ELMOD for the Rooikop (existing) runway pavement structure

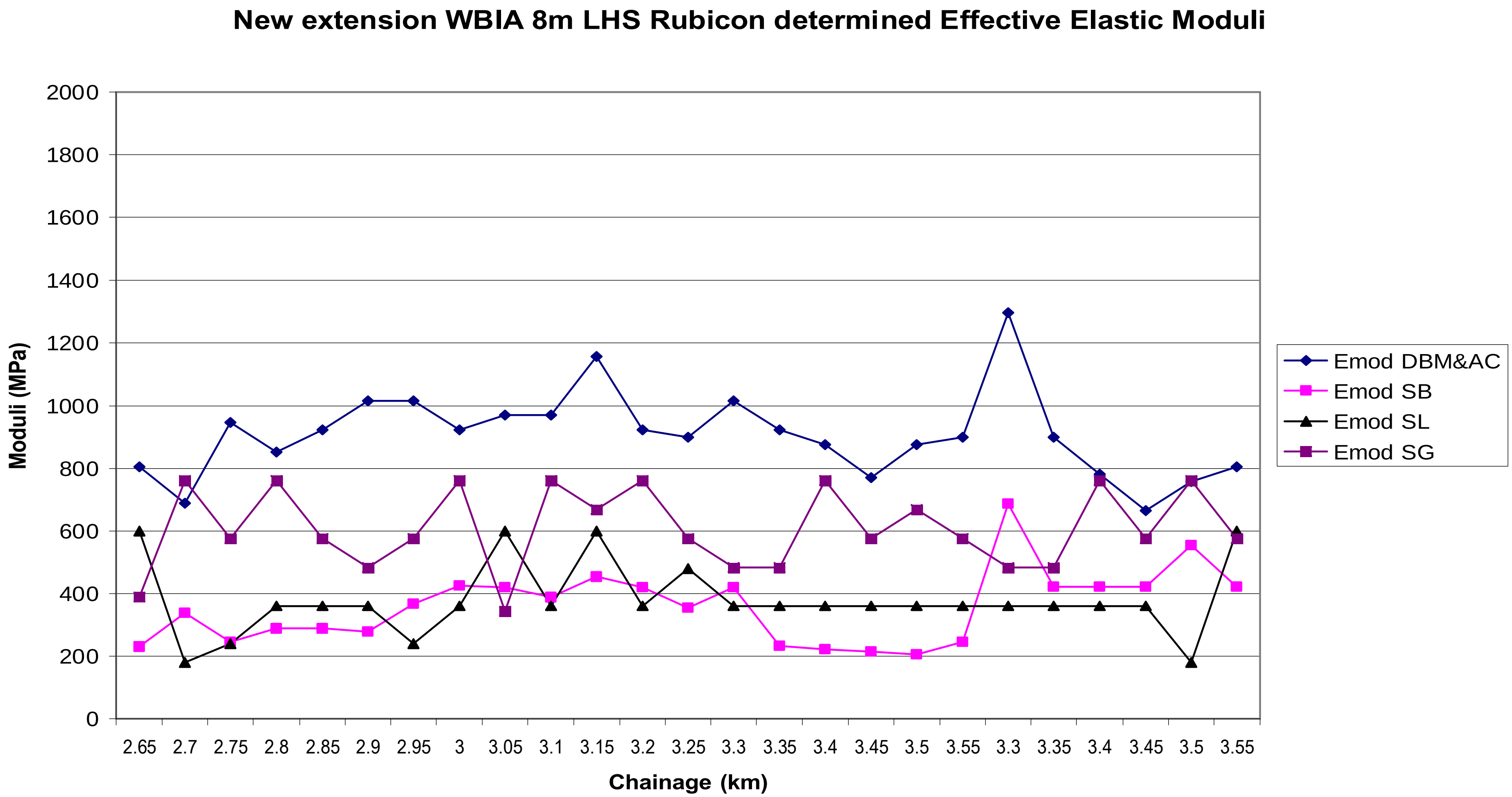


Existing pavement structure (Rooikop)

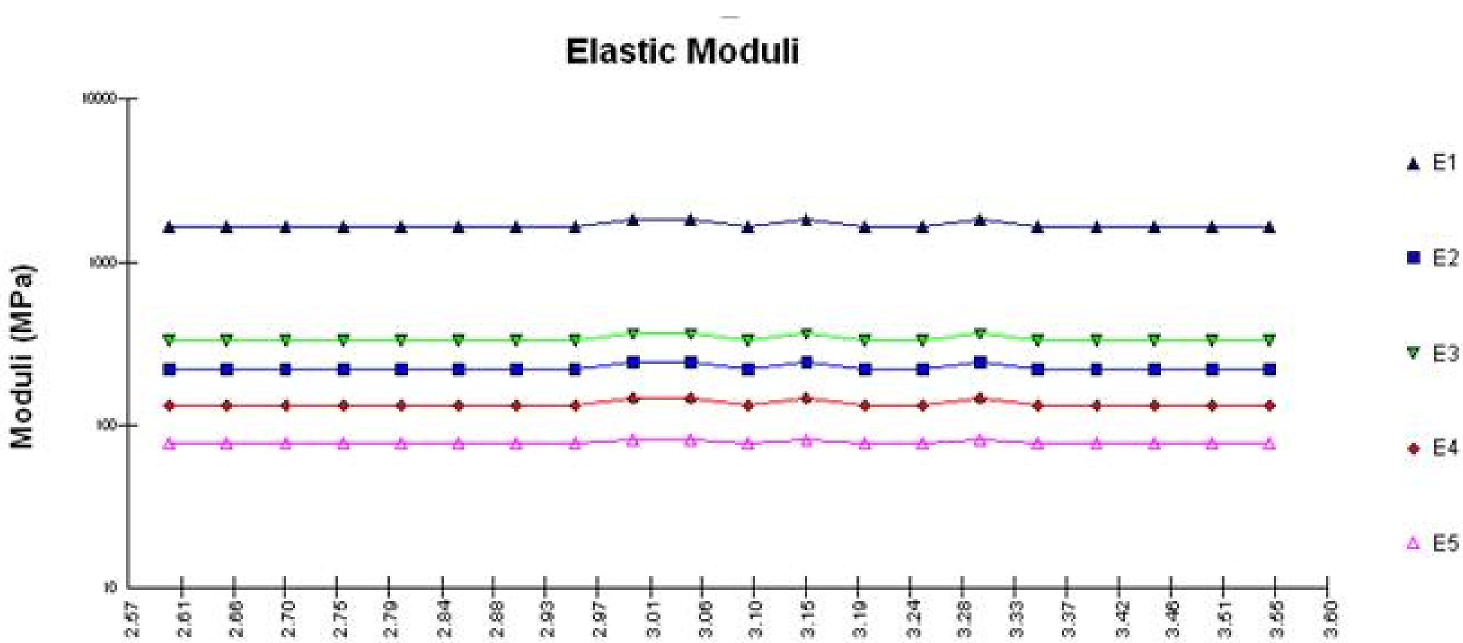
Layer	Thickness	Previous Effective Elastic Moduli (MPa)	Layer identification
Asphalt	90mm	2000	E1
WM base	100mm	500	E2
Sub-base	150mm	450	E3
Selected	300	190	E4
Subgrade	Semi-infinite	90	E5



Old section of WBIA (Rooikop) needs no structural strengthening (overlay)

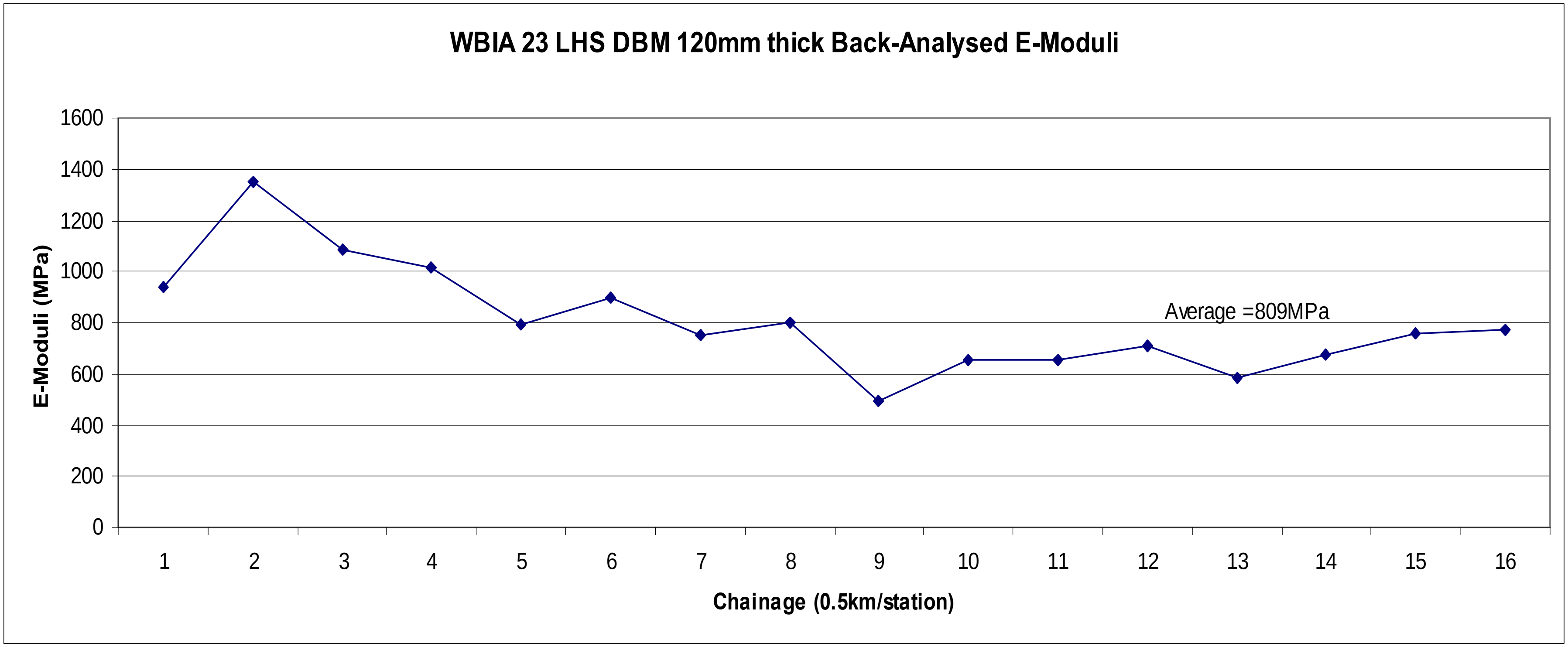


Using Rubicon software to do back-calculations



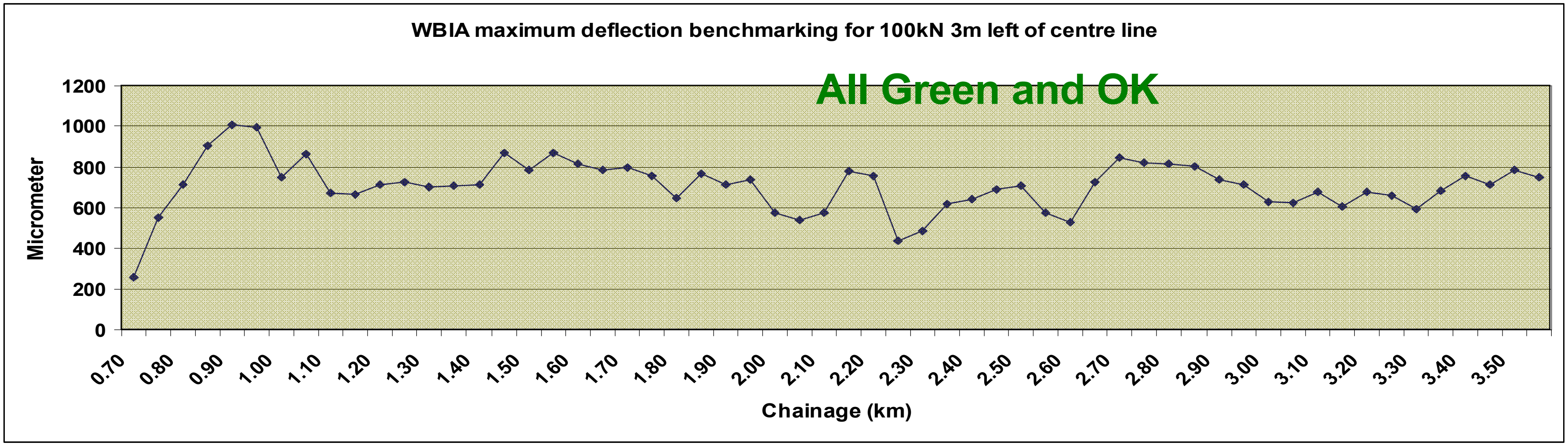
Average values of effective elastic moduli back-calculated for new keel area under construction

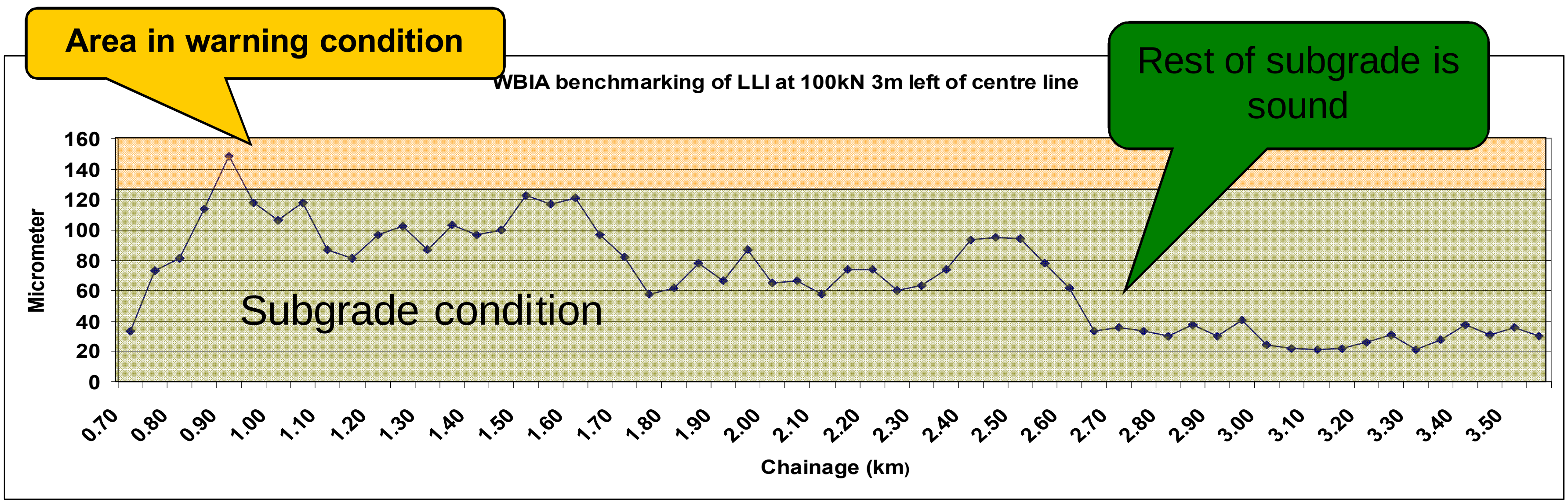
Layer	Thickness	Previous* Effective Elastic Moduli (MPa)	ELMOD back calculated value (MPa)	Layer identification
Scratch coat	30mm	1500	1650	E1
DBM base	150mm	450	220	E2
Sub-base	425mm	500	330	E3
Selected	300mm	150	145	E4
Subgrade	Semi-infinite	80	80	E5

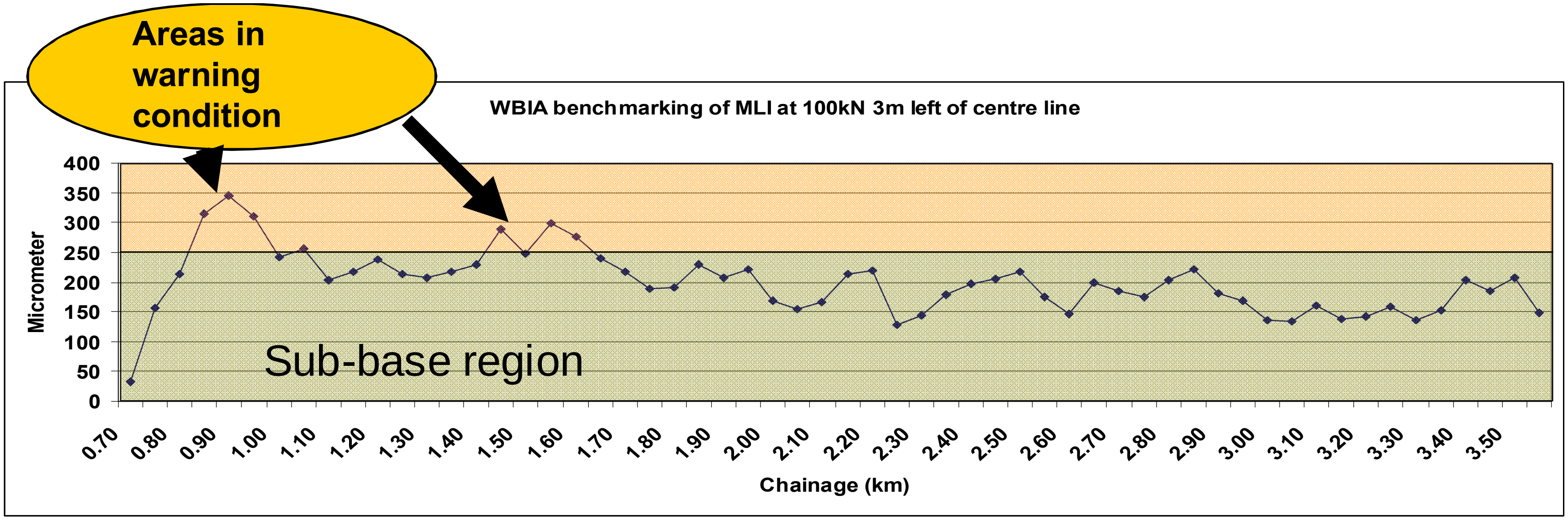


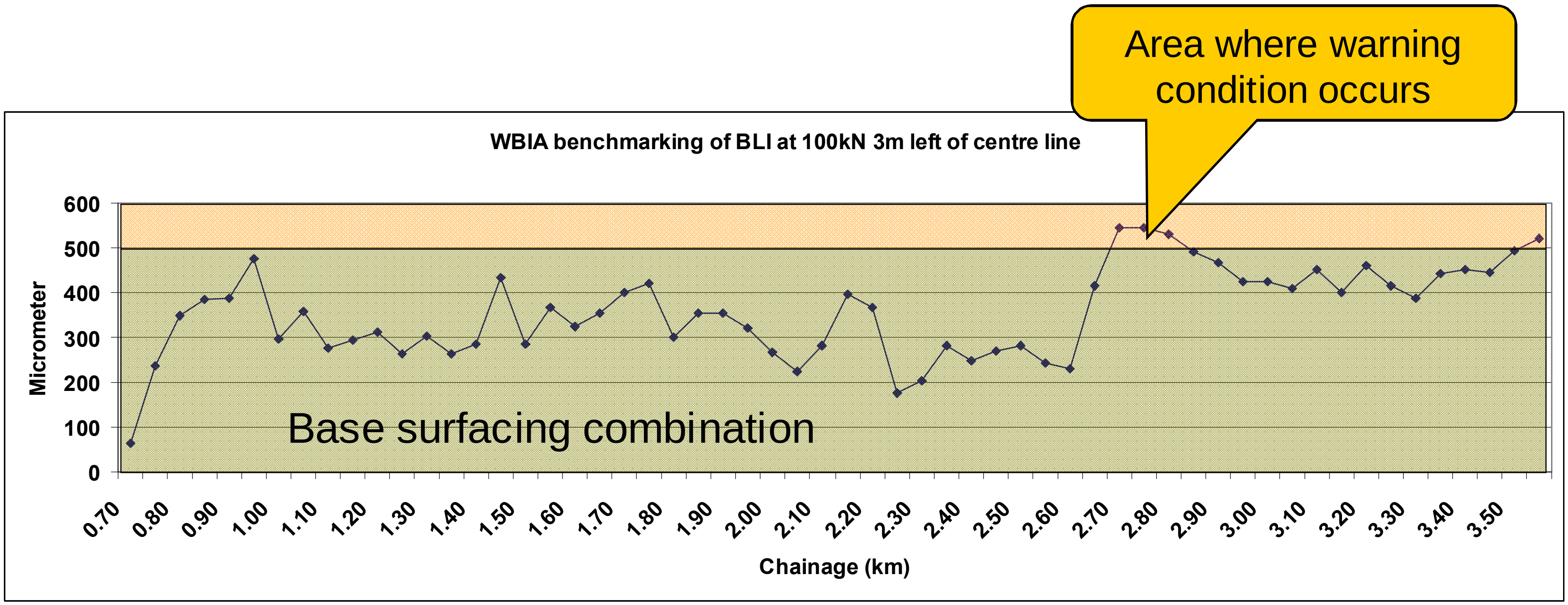
Effective elastic moduli back-calculated with Rubicon of Dry-bound Macadam base layer alone

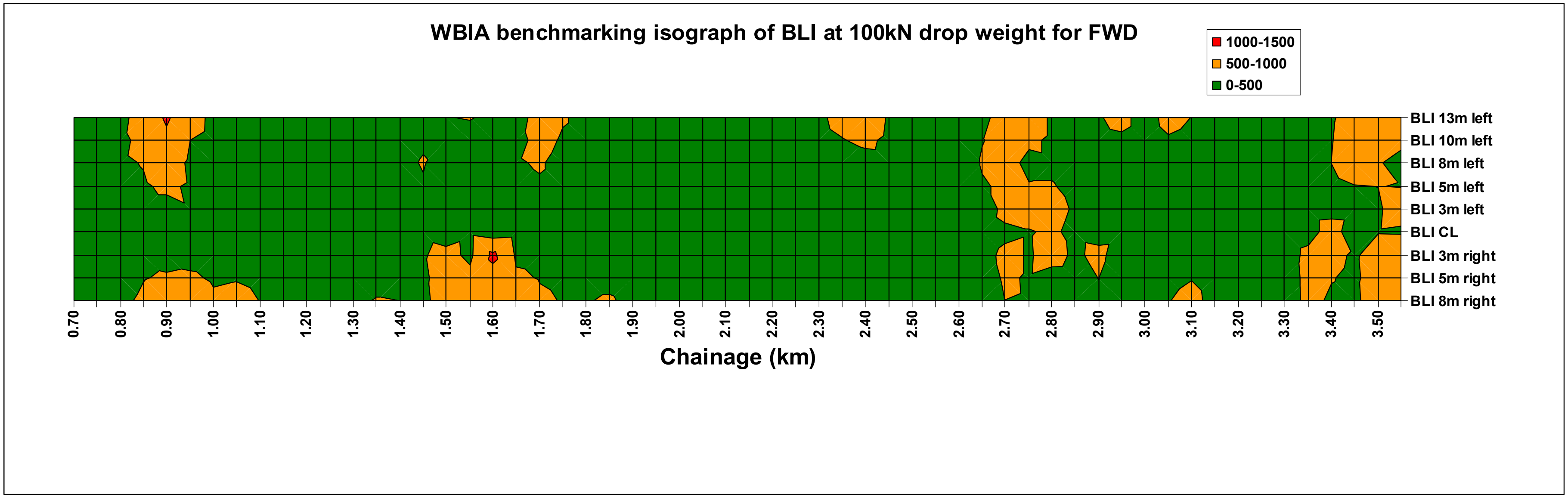
WBIA applying deflection bowl parameter benchmarking





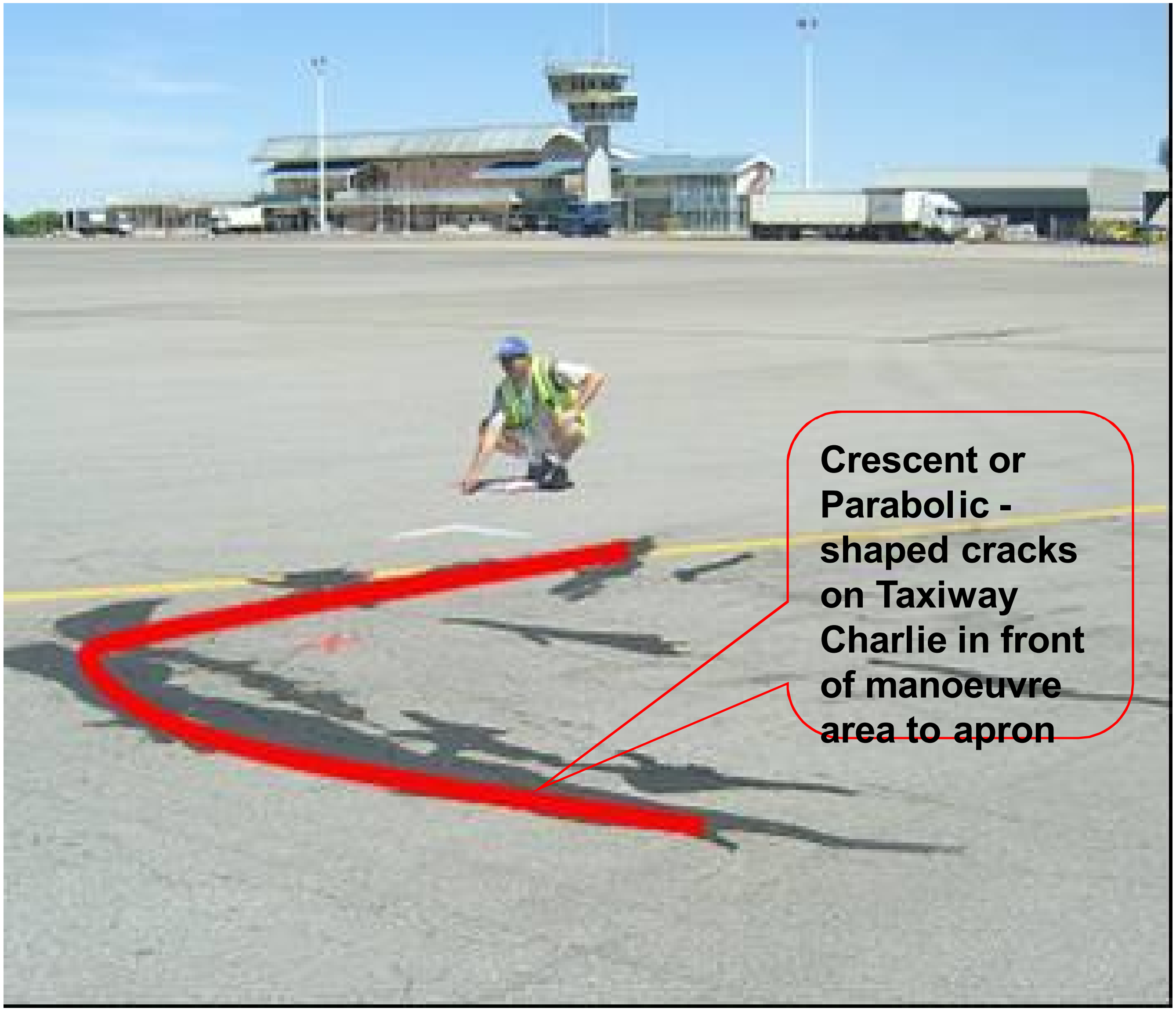

Areas in warning condition
WBIA benchmarking of MLI at 100kN 3m left of centre line
Micrometer
400
350
300
250
200
150
100
50
0
Sub-base region
0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10 3.20 3.30 3.40 3.50
Chainage (km)


Area where warning condition occurs
WBIA benchmarking of BLI at 100kN 3m left of centre line
Micrometer
600
500
400
300
200
100
0
Base surfacing combination
0.70 0.80 0.90 1.00 1.10 1.20 1.30 1.40 1.50 1.60 1.70 1.80 1.90 2.00 2.10 2.20 2.30 2.40 2.50 2.60 2.70 2.80 2.90 3.00 3.10 3.20 3.30 3.40 3.50
Chainage (km)

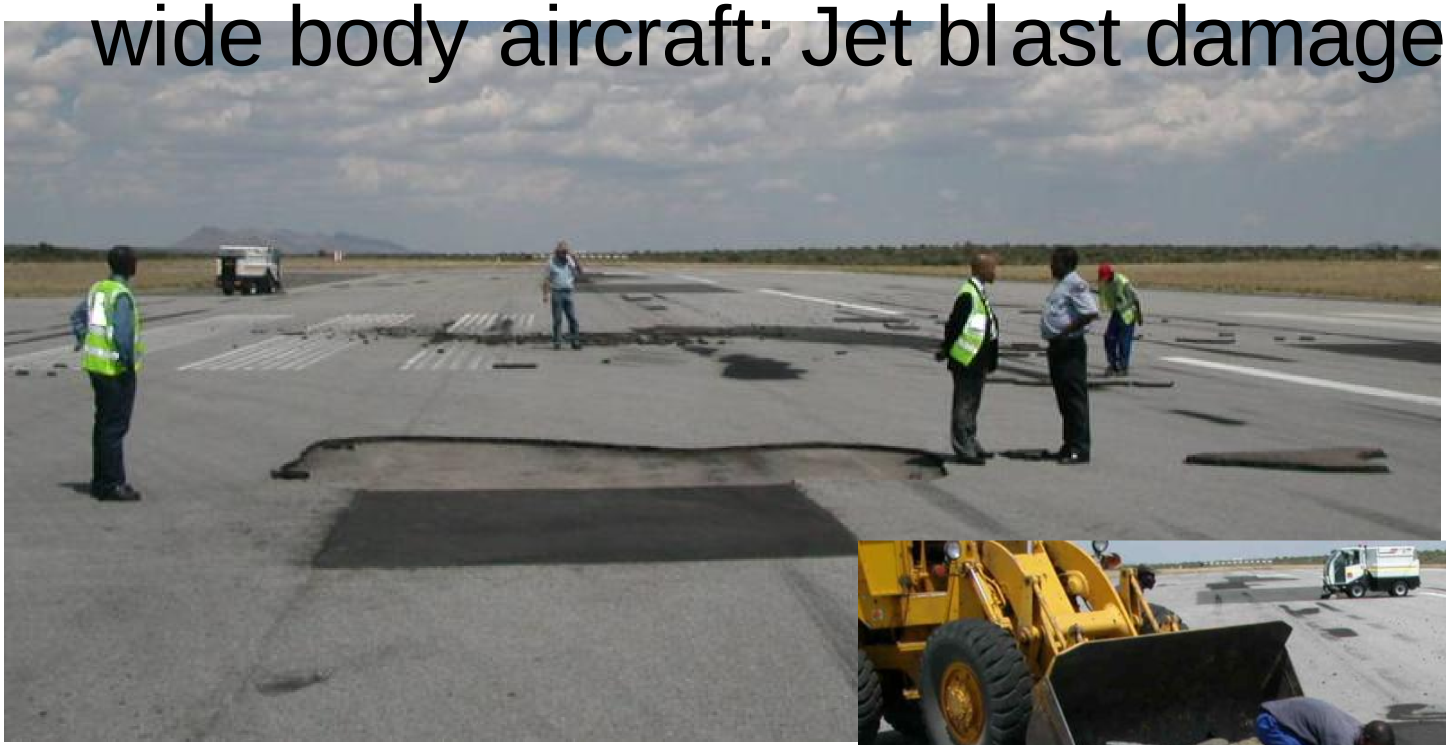


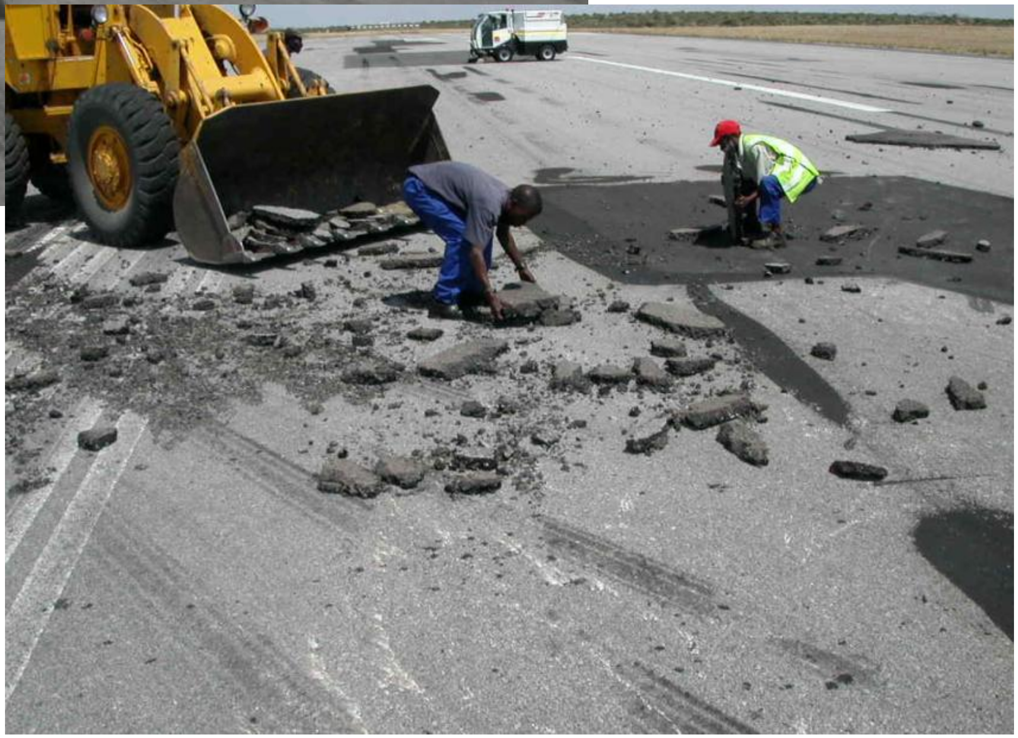
BLI Isograph identifying all area where base/surfacing combination may be in warning condition


Hosea Kutako International Airport (HKIA)
40km outside Windhoek, Namibia
© 2007 Europa Technologies
Image © 2007 DigitalGlobe
Google
Pointer 22°29'06.56" S 17°28'13.92" E elev 1697 m
Streaming 1%
Eye alt

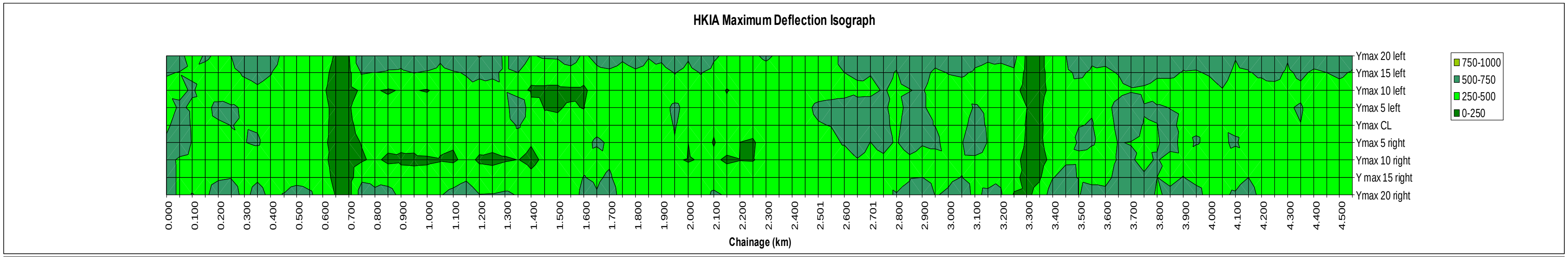

Crescent or Parabolic - shaped cracks on Taxiway Charlie in front of manoeuvre area to apron

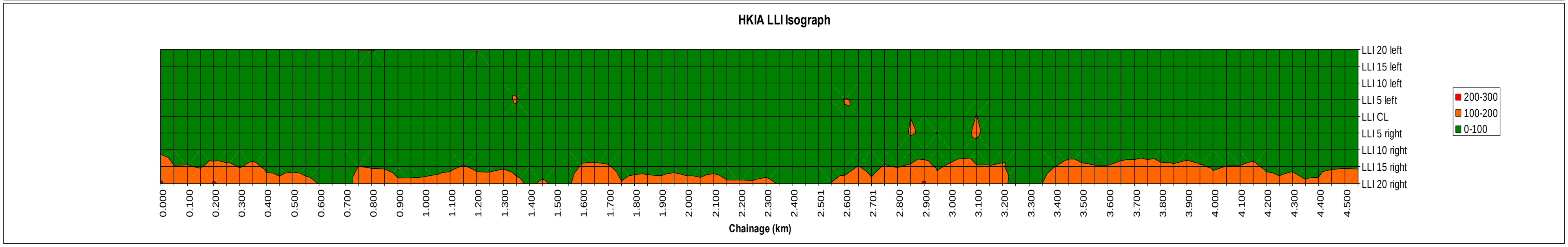
Delamination due to shearing and shoving of wide body aircraft: Jet blast damage

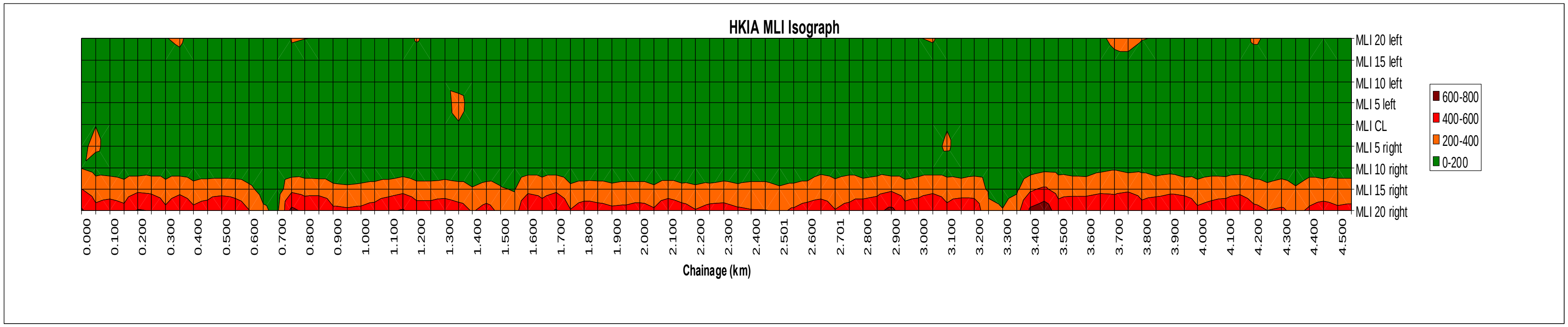


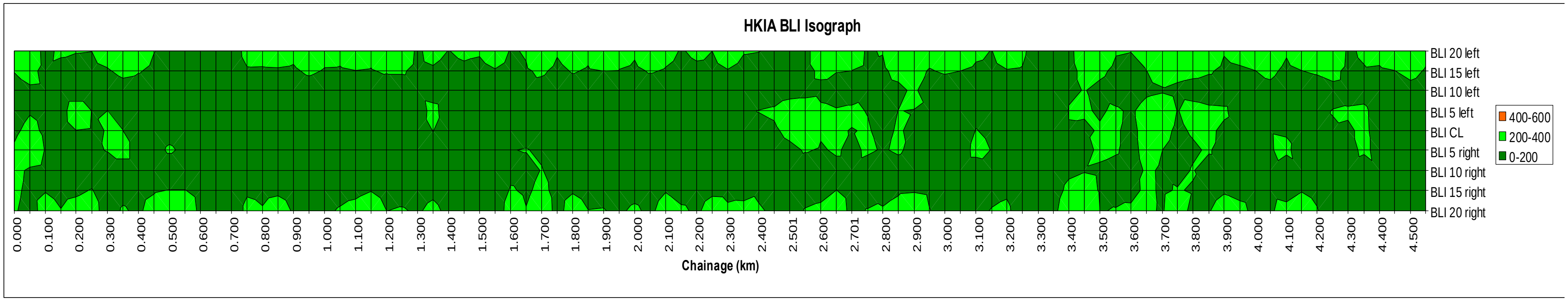


Delaminated areas where upper layer can be lifted by spade

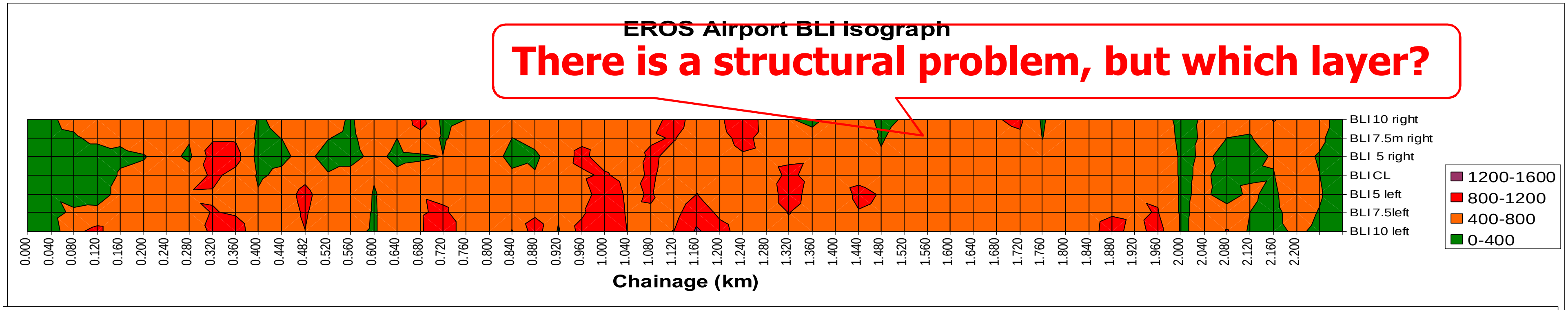

HKIA Maximum Deflection Isograph
Ymax 20 left
Ymax 15 left
Ymax 10 left
Ymax 5 left
Ymax CL
Ymax 5 right
Ymax 10 right
Y max 15 right
Ymax 20 right
750-1000
500-750
250-500
0-250
Chainage (km)

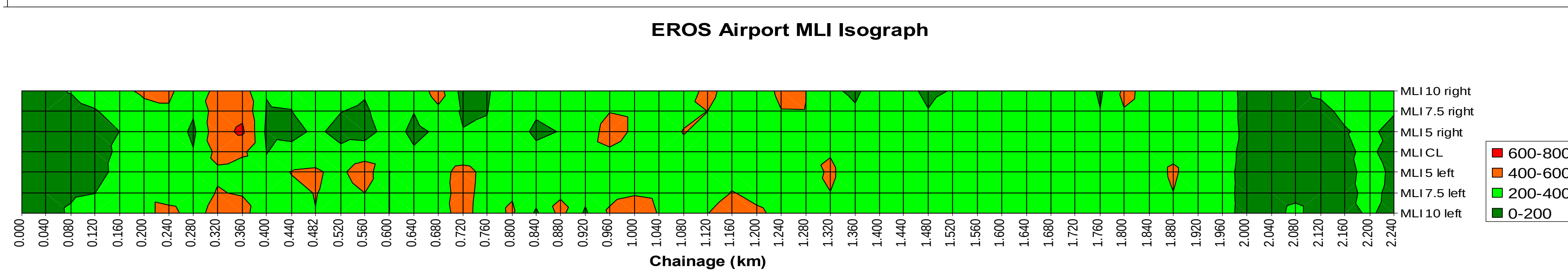

HKIA LLI Isograph
LLI 20 left
LLI 15 left
LLI 10 left
LLI 5 left
LLI CL
LLI 5 right
LLI 10 right
LLI 15 right
LLI 20 right
200-300
100-200
0-100
Chainage (km)

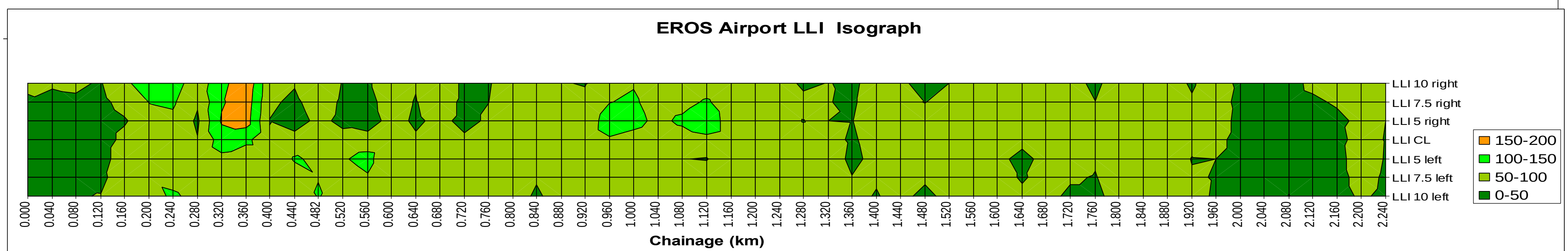

HKIA MLI Isograph
MLI 20 left
MLI 15 left
MLI 10 left
MLI 5 left
MLI CL
MLI 5 right
MLI 10 right
MLI 15 right
MLI 20 right
600-800
400-600
200-400
0-200
Chainage (km)

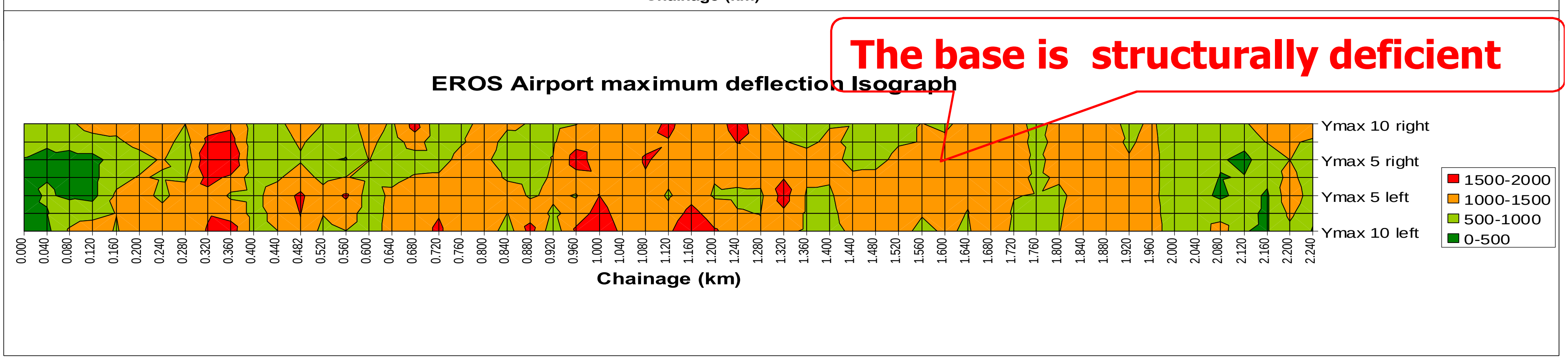

HKIA BLI Isograph
BLI 20 left
BLI 15 left
BLI 10 left
BLI 5 left
BLI CL
BLI 5 right
BLI 10 right
BLI 15 right
BLI 20 right
400-600
200-400
0-200
Chainage (km)

Eros Domestic Airport in Windhoek, Namibia. Recent FWD survey done on main runway to identify structural capacity problems


EROS Airport BLI isograph
There is a structural problem, but which layer?
BLI 10 right
BLI 7.5m right
BLI 5 right
BLI CL
BLI 5 left
BLI 7.5left
BLI 10 left
1200-1600
800-1200
400-800
0-400
Chainage (km)


EROS Airport MLI Isograph
MLI 10 right
MLI 7.5 right
MLI 5 right
MLI CL
MLI 5 left
MLI 7.5 left
MLI 10 left
600-800
400-600
200-400
0-200
Chainage (km)

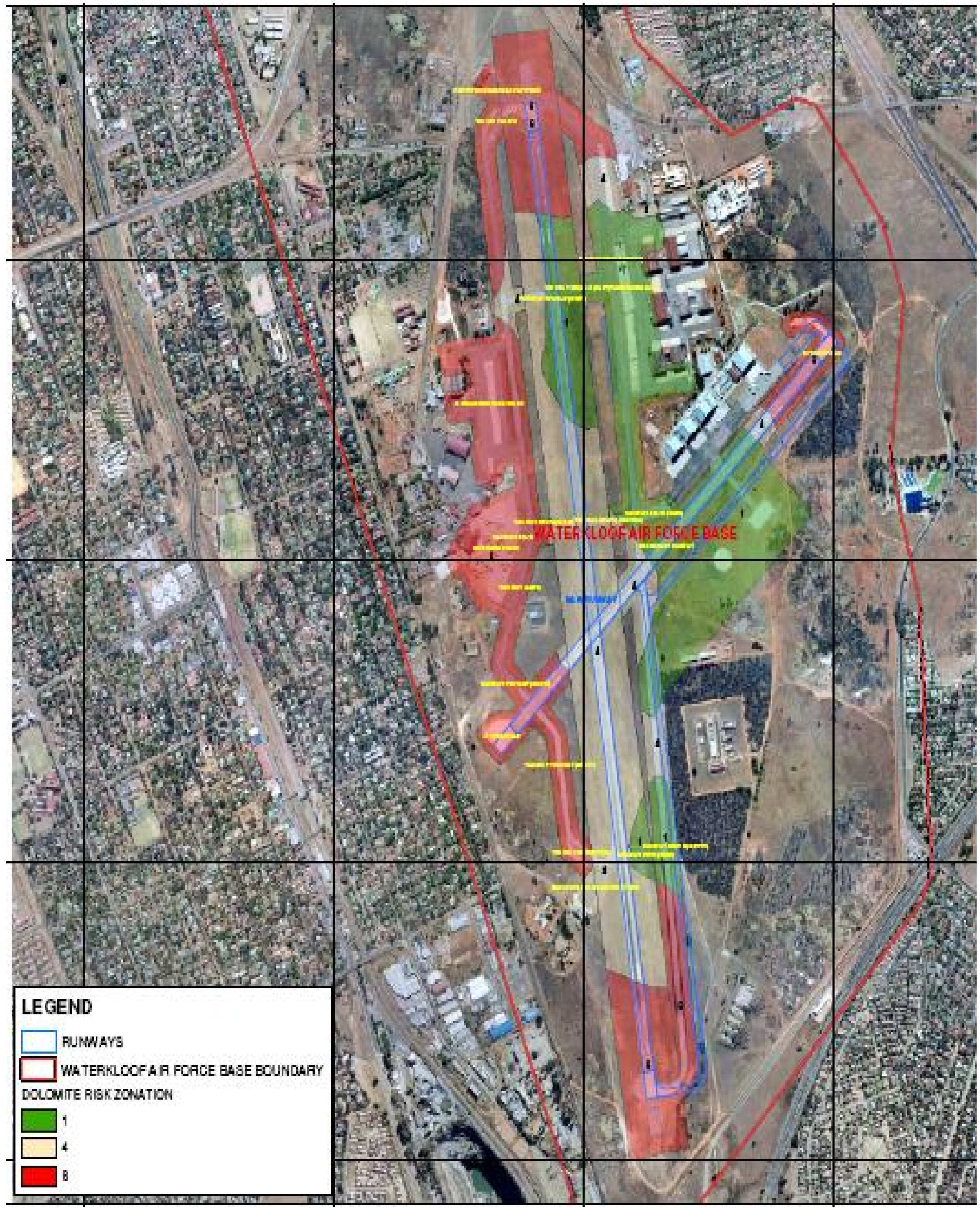

EROS Airport LLI Isograph
LLI 10 right
LLI 7.5 right
LLI 5 right
LLI CL
LLI 5 left
LLI 7.5 left
LLI 10 left
150-200
100-150
50-100
0-50
Chainage (km)

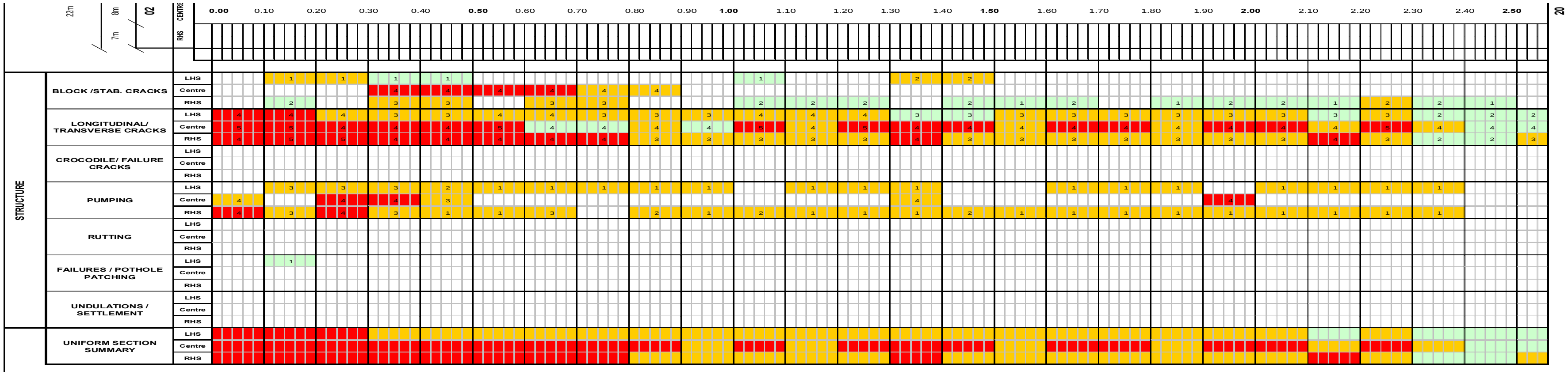

The base is structurally deficient
EROS Airport maximum deflection Isograph
Ymax 10 right
Ymax 5 right
Ymax 5 left
Ymax 10 left
1500-2000
1000-1500
500-1000
0-500
Chainage (km)

Waterkloof Airforce Base , Pretoria, South Africa

Rehabilitation and upgrade of runways and taxiways

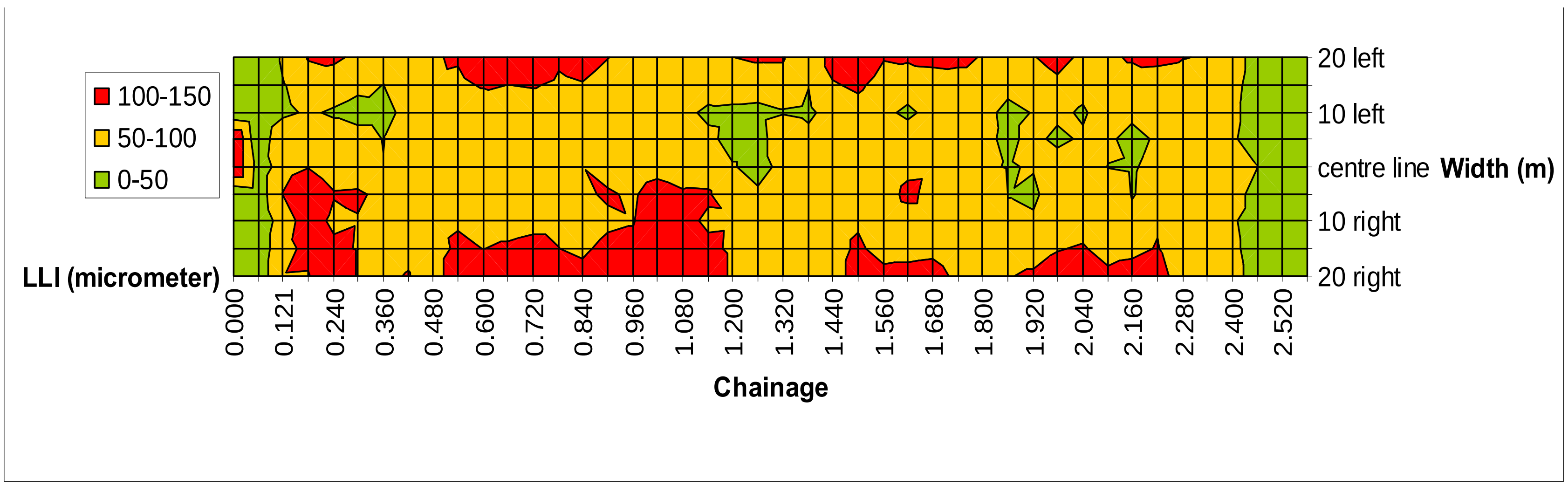
Major problems with dolomitic sinkhole formation





Visual condition rating using RAG system to rate runway condition

FWD deflection bowl parameter benchmarking confirmed most of the distress observed originate from the subgrade



Conclusions

- Empirical relations of maximum deflection only may give misleading answers of pavement structural strength
- Linear elastic multi-layered elastic modelling has some credibility problems if used with back-calculation procedures in the hands of the lesser informed
- The identified zones on actual measured deflection bowls correlate well with the structural zones and response of a pavement structure
- The RAG system of structural condition rating as used on road pavement visual condition rating is well calibrated with accelerated pavement testing
- This RAG system can be used to benchmark zones in the pavement structure on a comparative basis
- Extrapolation the linear elastic response allows for credible use of the RAG deflection bowl parameter system with airport pavement structures