IMPORTANCE OF THE ZERO POINT IN DCP TESTING OF STRUCTURAL CAPACITY OF FLEXIBLE PAVEMENTS

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ABSTRACT

Relatively large errors attributable to the use of an incorrect position of the zero point may occur in estimates of pavement structural capacity and other parameters using DCP methods.

The standard South African method requires the zero reference point to be taken with the top of the vertical shoulder of the cone level with the top of the surfacing of the pavement.

However, the Kleyn granular pavement model of analysis was developed from DCP testing in which the zero point was taken at the top of the base course.

The De Beer lightly cemented pavement model was developed using DCP tests in which the zero point was taken at the top of the surfacing.

In many cases these differences may not be significant. However, those which are likely to be include old pavements with thick, hard surfacings and new pavements with soft, bleeding seals.

Those aspects which are most severely affected are the DCP structural number and estimates of the strength of the upper pavement, structural capacity and relative damage exponent, whilst the obtained structural balance of the pavement may also be affected.

It is not the purpose of this paper to review or cast aspersions on previous work, but only to show the importance of selecting the correct zero point for the analysis model used.

Two case histories of a total of 15 different, mostly granular pavements with old seals and one of 15 single point analyses on one new, cemented base pavement with a new, bleeding seal are presented.

In the case of the old pavements analysed according to the granular model significantly higher estimates of structural number, structural capacity, strength of the “base” and relative damage exponent were obtained by including the seal.

In the case of the new pavement analysed according to the cemented model significantly higher estimates of structural capacity were generally obtained when the seal was excluded.

Until a more authoritative and detailed analysis is available it is recommended that, in cases of doubt, the DCP software program be run both with and without the surfacing and the more conservative results used.

1. INTRODUCTION

Hand-operated dynamic cone penetrometer (DCP) testing has been an important part of pavement evaluation in South Africa for many years (e.g. Kleyn, 1975; Kleyn et al, 1982; De Beer, 1991; Paige-Green, 2011).

The test is simple, almost non-destructive, inexpensive, was standardised over 30 years ago in TMH 6: 1984 (National Institute for Transport and Road Research (NITRR), 1984) and guidelines for its interpretation and application included in the national code of practice on pavement rehabilitation investigation and design (TRH 12: 1997 – Committee of Land Transport Officials, (COLTO) 1997).

The results of DCP testing can be interpreted manually during or after testing or, more usually, using a computer software program such as WinDCP 5.1 (CSIR, 2012).

It is not the purpose of this paper to provide a general review of DCP testing and interpretation or to cast aspersions on the valuable work quoted, but simply to raise awareness of the importance of the DCP zero reference point adopted by the user which in certain cases can seriously affect the results, and which appears to have been overlooked or regarded as unimportant. Other aspects are not considered and for the purpose of this paper some of the limitations of the models used have been ignored.

Three case histories are presented: Twelve different types of mostly stabilized sand – but now mostly effectively granular – base courses under a relatively thick, hard, 55 year-old triple seal, one untreated and one cement-treated gravel base under a 30 year-old double seal, and a new cement/emulsion-treated gravel base under a soft, bleeding Cape seal.

2. ANALYSIS MODELS USED

The standard method of carrying out the DCP test at the NITRR since the early 1970s and adopted as the South African standard method in TMH 6 : 1984 (NITRR, 1984) requires that the zero reference point is taken when the top of the vertical part of the cone shoulder is level with the **top of the** "**surface"**. [Author's embolding in all cases.]

According to Paige-Green and Du Plessis (2009) it is taken when it is "flush with the surface of the **layer** being tested." The ASTM procedure is effectively the same: "For pavements with thin seals, the tip is advanced through the seal until the zero point……..of the tip is flush with the top of the **layer** to be tested" (ASTM D6951 / D6951M-9 : 2015). The author finds this use of the term 'layer' to be confusing, as the whole pavement, i.e. all layers, is usually evaluated in a single penetration

The two empirically-derived models most commonly used in South Africa for the analysis of DCP test results were used: the granular and the cemented pavement models, both as provided in the WinDCP programs (CSIR, 1998; 2012).

All of the testing used in the development of Kleyn's granular pavement model (e.g. Kleyn, 1975; Kleyn and Savage, 1982; Kleyn and Van Zyl, 1988) was carried out with the zero point at the **top of the base** course (EG Kleyn, 1998, 2018, pers. comm.), and "the curve drawn from the underside of the surface course (at say 20 mm) to a depth of 800 mm" (Kleyn, 1975), any contribution of the surfacing being regarded as a bonus.

According to De Beer et al (1989) the DCP pavement structural number for a depth of 800 mm (DSN_{800}) is the "total number of blows to penetrate 800 mm of the **pavement**" and the BN_{100} is the "percentage of blows to penetrate the **top** 100 mm of the **pavement**", whilst CSIR (1998) stated clearly that the DSN_{800} is **taken** from "the **surface of the pavement**, implying that the seal (or part thereof) is **included.**

Although in the layer strength diagrams shown a relatively thin seal may have been omitted, in neither work nor the supporting papers accompanying the WinDCP 4.0 manual (CSIR, 1998) was it stated that the surfacing was to be excluded from the analysis.

The De Beer lightly cemented base model (De Beer, 1989; De Beer, et al 1989) was developed using DCP testing in which the zero point was taken at the **top of the (relatively thin) surfacing** as in TMH 6 : 1984 (M De Beer, 1998, 2018, pers. comm.).

The granular base model can be used on pavements with both granular and lightly cemented (unconfined compressive strength (UCS) < 3 000 kPa – CSIR, 1998) bases (Kleyn and Savage, 1982; TRH 12:1997) although it tends to overpredict the structural capacity of cemented pavements – sometimes seriously (De Beer et al, 1989).

The equations used in this paper are as follows:

- Structural capacity of granular pavements to an **additional** rut depth of 20 mm in millions of actual 80kN standard axle loads (MISA) (Kleyn and Savage, 1982; Kleyn, 1984; WinDCP 4.0 – CSIR, 1998):

  Capacity = $Cm \times 10^{-9} (DSN_{800})^{3.5}$……………………… MISA (1)

  Where :

  Cm = Moisture factor, here taken as 30 for moderate conditions

  DSN_{800} = DCP structural number, i.e. the total number of blows to a depth of 800 mm

  Limitations: Untreated, lightly cemented (< 3 MPa) - or bitumen-treated, balanced or nearly balanced pavements, 0,2 to 10 MISA (12 max.)

- Relative damage (TRH 4: 1996 – COLTO 1996) or load equivalency (Kleyn and Savage, 1982) exponent (LEE) :

- LEE = $0{,}044 (BN_{100})^{1{,}24}$…………………………… n (2)

  Where :

  BN_{100} = $100 (DSN_{100}/DSN_{800})$ .. ……………… % (3)

  DSN_{100} = Number of blows to a depth of 100 mm

- Structural capacity (SC_{20}) of cemented pavements in millions of equivalent 80kN standard axles (MESA) (De Beer, 1989; De Beer et al, 1989), recast from Netterberg and De Beer, 2012) to an **additional** rut depth of 20 mm :

$$SC_{20} = \left[\frac{10^{\left[\frac{3{,}83 - DN_{50}}{1{,}39}\right]} \times 20}{DSN_{200}} \right] \quad \text{……………………….. MESA} \quad (4)$$

Where:

DN_{50} = Average penetration rate in upper 50 mm of pavement, including thin seal (< 10 mm – M De Beer, 2018, pers. comm.) in mm/blow, penetration depth measured after every blow

DSN_{200} = Total number of blows in upper 200 mm of pavement, including thin seal (< 10 mm); penetration depth measured after every blow

Limitations: UCS of base 0,5 to 3 MPa, DSN_{800} 200 to 750 blows, B ≥ 0, and A ≤ 3 000 (De Beer, 1989; 1990); 20 mm maximum terminal rut depth, DN_{50} 0,5 to 4 mm/blow, ≤ 20 MESA (Netterberg and De Beer, 2012)

All DCP testing for the work presented here was carried out according to TMH 6: 1984 with the zero reference point at the top of the seal.

3. CASE 1 : 55 YEAR-OLD, THICK, HARD TRIPLE SEAL

This case consisted of a long-term pavement performance (LTPP) experiment on the Hoopstad-Bultfontein road in South Africa (Netterberg, 2017).

<u>Surfacing</u>: Triple seal constructed in 1962 with one chip reseal and one or two rejuvenation sprays of a total thickness of 25 to 30 mm.
<u>Base</u>: Eleven test sections of ordinary portland cement (OPC)-, portland blastfurnace cement (PBFC)-, sulphite lye-, bituminous emulsion-, and cutback tar- treated Kalahari sand with a neat Kalahari sand and a neat crusher-run control section. The neat sand base classified as a COLTO:1998 G7 material and the crusher-run as a G4. The cement-treated bases were probably originally equivalent to a COLTO C3
<u>Subbase</u>: 3 % PBFC-treated Kalahari sand of assumed original C4 quality
<u>Selected and lower layers</u>: Neat Kalahari sand (G7)

According to the TRH12 : 1997 criteria for falling weight deflectometer testing all of the pavements were either in a flexible or very flexible state and, according to phenolphthalein and acid testing (Netterberg, 1984), all the cement-treated layers were totally carbonated.

A thickness of 25 mm was entered into the WInDCP 5.1 software program for the first layer (i.e. the surfacing) and 150 mm for all other layers. The number of blows required to penetrate to 25 mm was used to correct both the DSN_{800} and BN_{100}. In most cases this 25 mm agreed approximately with the computer-redefined thickness of the seal. However, in other cases there were large discrepancies.

Table 1 summarises the effect of the position of the zero point of the DCP on the DCP pavement structural number (DSN_{800}), predicted residual structural capacity, and load equivalency exponent (LEE) on these sections.

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Table 1. Effect of zero point of DCP on mean pavement structural number, estimates of mean residual structural capacity and load equivalency exponent

Section	Units	A	B	C	D	E	F	G	HA	HB	JA	JB	K
Base / Parameters		Neat sand	3% OPC	5% OPC	10% OPC	5% PBFC	5% PBFC	2% Sulfite lye	8% Bit. emul.	4% Bit. emul.	4% Tar	8% Tar	Crusher -run
Balance [1]	-	ABD	ABI	ABD	PBD	ABI	PBD	ABD	PBD	PBD	PBD	PBD	PBD
DSN $_{800}$													
Incl. [2]	blows	205	248	172	244	214	314	249	299	238	313	341	475
Excl. [3]	blows	189	242	160	233	207	279	223	246	223	267	291	434
Capacity [4]													
Incl.	MISA	3,7	7,2	2,0	6,8	4,3	(16)	7,3	(14)	6,2	(16)	(22)	(70)
Excl.	MISA	2,8	6,2	1,6	5,8	3,8	(11)	5,0	7,0	5,0	9,3	(12)	(50)
Seal [5]													
Blows	no.	22	18	17	20	14	45	31	62	26	53	5,8	58
DN	mm/bl.	2,0	2,3	2,5	1,6	3,1	0,8	1,1	0,5	1,3	0,6	0,6	0,7
Base DN [6]													
Excl.	mm/bl.	6,8	5,2	5,4	2,7	6,0	2,3	4,7	3,5	4,0	3,8	2,9	1,0
LEE (n) [7]													
Incl. [8]	-	1,4	1,2	1,7	2,7	1,1	3,2	1,8	3,2	2,1	2,5	3,7	3,5
Excl. [9]	-	0,6	0,7	1,1	3,0	0,7	2,1	0,9	1,8	1,3	1,0	2,1	3,2
Tests [10]	no.	4	3	3	4	4	4	4	3	3	3	3	4

Notes:

[1] Including seal; AB = Averagely balanced, P = Poorly, D = Deep, I = Inverted, structure
[2] DSN_{800} from top of seal
[3] DSN_{800} from top of base = $DSN_{825} – DSN_{25}$
[4] Eq. 1. Figures bracketed have been extrapolated beyond the range of the method
[5] Seal thickness of 25 mm assumed in analysis (25 – 30 mm measured). Weighted average DN calculated by computer.
[6] Arithmetic average of 150 mm calculated manually
[7] BN_{100} including surfacing recalculated manually: $BN_{100} = DSN_{100} / DSN_{800} \times 100$
[8] Eq. 2
[9] BN_{100} excluding surfacing calculated manually : $BN_{100} = (DSN_{125} – DSN_{25}) / DSN_{825} – DSN_{25}) \times 100$
[10] Number of individual DCP sites averaged

The results show that, as expected, when excluding the seal all three parameters were invariably lower – often substantially so – than those with the old and brittle seal. This was essentially due to the subtraction from the DSN_{800} of the substantial number of blows necessary to penetrate the seal. Most seriously, the predicted capacities were presumably overestimated – usually by about 0,5 - 1 MISA – when the zero was taken at the top of the seal, as required by TMH6: 1984, in comparison with taking it at the top of the base.

As the seal was removed in the work carried out to develop the Kleyn model (Eq. 1) this should be the correct procedure to use. However, in this case the thick seal may well have contributed to the relatively good performance of these pavements.

Note : Manual checking of the computer-calculated BN_{100} balance parameters with the seal showed that the average values for groups of DCP test results were incorrect. This was found to be due to a program error, which wrongly showed the BN_{100} for the last single entry as the average, which has since been corrected in the new draft WinDCP 6.0 software (M de Beer, 2017, pers. comm.). Both these and those without the seal were therefore calculated manually. However, the results for single point analyses were correct. The LEE was calculated manually from the average BN_{100}.

The traffic load sensitivity of the pavement as indicated by the LEE (relative damage exponent) (n) was also affected by the position of the zero point.

This effect was also substantial and with one exception (Section D with 10% OPC) the exponent was invariably lower – often by as much as one half – when the seal was excluded, as in the Kleyn model.

The LEEs were mostly relatively low, tended to increase with the strength of the base course and were in general agreement with those shown in TRH 4:1996 Table 8, including the post-cracked phase of cemented pavements. However, the validity of exponents of less than unity is questionable and those determined including the seal appear more reasonable.

Whilst not shown in Table 1 it is also clear from the far lower DNs of the seal that erroneously low DN values and therefore high strengths for the upper 150 mm of the pavement would be obtained if the effect of this relatively thick seal was not removed.

Although not evaluated in detail, it was also clear that the obtained structural balance of the pavement would also be affected by the position of the DCP zero point.

4. CASE 2 : 30 YEAR-OLD DOUBLE SEAL

This case consisted of a LTPP experiment on the Coligny-Biesiesvlei road in South Africa (Netterberg, 2015).

Surfacing: Double seal constructed in 1976 with one slurry reseal and one chip reseal, but no rejuvenation sprays, of a total thickness of 13 to19 mm
Base: One untreated calcrete gravel base test section of G6 quality with two 4 % PBFC-treated calcrete gravel control sections of assumed original C3 quality
Subbase: 2 % PBFC-treated calcrete gravel of assumed original C4 quality

Selected and lower layers: G7 and G9 soil

All of the cement-treated layers were almost totally carbonated.

Table 2 summarises the effect of the position of the zero point of the DCP on the DSN_{800}, predicted structural capacity, BN_{100} and LEE of the remaining good parts of the untreated section and, for comparison, the right outer wheelpath of one of the cement-treated base (CTB) sections (recalculated from Netterberg, 2015).

Again, the effect of taking the zero point at the top of the seal was presumably to overestimate the structural capacity by 0,4-1,5 MISA, the strength of the base by up to 0,5 DN, and the LEE by up to 0,5.

Table 2. Effect of DCP zero point on mean pavement structural number, estimates of structural capacity and load equivalency exponent of two gravel-base pavements

Position / Parameter		Units	Untreated base				CTB
			Left lane		Right lane		
			OWP	IWP	IWP	OWP	OWP
Balance (incl. seal)	[1]		ABD	ABD	WBD	WBD	ABD
DSN_{800}							
Incl. seal	[2]	blows	277	272	221	185	246
Excl. seal	[3]	blows	259	260	210	176	232
Capacity	[4]						
Incl. seal		MISA	(11)	10	4,8	2,6	7,0
Excl. seal		MISA	8,4	8,5	4,0	2,2	5,7
Seal							
Existing							
Thickness		mm	15	15	15	15	15
Blows		no.	20	14	13	11	16
DN	[5]	mm/bl.	0,8	1,1	1,2	1,4	0,9
Redefined							
Thickness		mm	8	40	40	8	24
Blows		no.	15	28	24	7	21
DN	[6]	mm/bl.	0,8	1,7	2,0	1,6	1,5
“Base“ DN							
Incl. (0-150 mm)	[6]	mm/bl.	2,4	1,8	2,3	3,5	2,8
Excl. (15-165 mm)	[5]	mm/bl.	1,9	1,3	2,1	3,5	2,5
Excl. (Redefined)	[6]	mm/bl.	2,5	2,0	2,4	3,6	4,4
Excl.(Red. depth)		mm	9 -152	41-184	41-152	9 -176	25-536
BN_{100}	[7]						
Incl. (0-150 mm)	[8]	%	21,3	34,9	28,1	20,0	22,0
Excl. (15-165 mm	[8]	%	17,4	35,4	25,7	17,6	19,0
LEE	[9]						
Incl. seal		n	2,0	3,6	2,8	1,8	2,0
Excl. seal		n	1,5	3,7	2,5	1,5	1,7
Tests	[10]	no.	7	3	2	6	6

Notes:
[1] AB = Averagely Balanced, W = Well, D = Deep, structure [2] DSN_{800} from top of seal [3] DSN_{800} from top of base = DSN_{815} – DSN_{15} [4] Eq. 1 [5] Arithmetic average calculated manually [6] Weighted average calculated by computer [7] Eq. 3 [8] Recalculated manually [9] Eq. 2 [10] Number of individual DCP sites averaged

5. CASE 3: NEW CAPE SEAL

This case is based upon a section of a new road which had to be closed within one week of opening due to shallow base shear failures and severe punching and bleeding caused by a weak interlayer between the Cape seal and the base course (Netterberg, in preparation).

Surfacing: 19 mm Cape seal with crusher-dust asphalt
Base and subbase: 2 : 1 Mix of finely graded calcrete and Kalahari sand with 2,5 % CEM 1 42,5 and 1,5 % SS60, 300 mm thick, as a C3 on a C4
Selected and lower layers: Neat Kalahari sand (G7)

Table 3 shows a comparison of the results of some of the DCP tests analysed using the cemented pavement model both including the seal and excluding it by utilizing the WinDCP 4.0 (CSIR, 1998) computer-redefined pavement structure, arranged in order of decreasing DN_{50}, i.e. increasing strength of the uppermost 50 mm of the pavement.

Table 3. Effect of DCP zero point on single point estimates of structural capacity by the cemented pavement model

Site No.	km	Position	0 to 50 mm (Seal included)			DCP – Redefined (Seal excluded)			
			DN_{50}	DSN_{200}	Capacity	Depth	DN_{50}	DSN_{200}	Capacity
			mm/bl.	blows	MESA[2]	mm	mm/bl.	blows	MESA[2]
1	2+129	OWP	7,69	42	0,0008	15-65	8,33	43	(0,0003)
2	13+120	OWP	7,14	65	0,001	15-65	5,56	65	0,017
3	2+158	OWP	6,67	41	0,004	15-65	6,25	40	0,009
4	6+428	OWP	6,25	67	0,005	15-65	5,00	66	0,043
5	2+165	OWP	6,25	33	0,01	15-65	7,14	32	0,003
6	7+935	OWP	5,88	55	0,01	10-60	6,25	56	0,006
7	13+120	OWP	5,56	93	0,01	20-70	3,85	97	0,20
8	8+950	IWP	5,56	30	0,04	15-65	6,25	29	0,01
9	6+270	OWP	5,00	77	0,04	15-65	4,17	80	0,14
10	13+120	SH	5,00	96	0,03	15-65	3,33	99	0,46
11	2+165	SH	4,55	84	0,07	15-65	3,13	87	0,74
12	13+120	IWP	3,85	64	0,30	5-55	4,17	63	0,18
13	6+270	SH	3,70	77	0,32	5-55	3,57	77	0,40
14	6+428	OWP	3,57	95	0,32	15-65	2,78	101	1,1
15	2+165	IWP	2,63	111	1,3	15-65	2,08	112	3,2

Notes:
[1] OWP = Outer Wheelpath, IWP = Inner Wheelpath, SH = Shoulder (sealed)
[2] Extrapolated for DN_{50} > 4 mm/blow as in Netterberg and De Beer (2012)

In this case excluding the soft seal generally resulted in significantly higher capacity predictions due to the lower resultant DN_{50}.

Those five sites which yielded a lower capacity all yielded a higher DN_{50} on removal of the soft seal in spite of a similar DSN_{200}, confirming the overriding importance of the strength of the upper 50 mm.

Note: The position of the zero reference point will also influence the results yielded by De Beer's (1992; Litwinowicz and De Beer, 2013) method of predicting the crushing life span of cemented pavements in relation to the tyre contact stress and the in-situ DCP-derived UCS, as well as any other DCP-based design method.

6. CONCLUSIONS

When analysed using the granular pavement model the effect of taking the DCP zero reference point at the top of the surfacing as required in TMH6: 1984 resulted in significantly higher estimates of structural capacity for all of the 15 mostly granular pavements with an old, hard seal analysed, and practically all for "base" course strength and the pavement relative damage exponent than when it was taken at the top of the base course, i.e. with the seal removed.

When analysed using the cemented pavement model the effect of taking the zero point at the top of the surfacing generally resulted in significantly lower estimates of structural capacity for the one cemented pavement with a new, soft seal analysed.

The correct procedure is apparently always to take the zero at the top of the base when analysis using the granular model is intended and the top of a thin surfacing in the case of the cemented model, and this approach generally yielded the more **conservative** predictions.

Which procedure actually yields the more **accurate** DCP-based predictions of structural capacity and damage exponent is beyond the scope of this paper. In the interim the more conservative procedure should be used.

As a standard general procedure allowing for both models the DCP test should always be started with the zero reference point at the top of the surfacing as in TMH 6 :1984. In the case of the granular model the zero point should usually be corrected to the top of the base course either manually or by using the computer-redefined case. However, the latter must always be inspected for reasonableness.

The position of the zero point selected will also affect the obtained structural balance of the pavement and estimates of the number of tyre repetitions required to cause crushing failure of a cemented base.

In short, whatever analysis model or design method is used the DCP zero point used should always be the same as that used to develop the method.

The average BN_{100} balance number for a series of DCP tests as calculated by WINDCP 5.1 is currently incorrect due to a program error and must be checked manually.

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