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Modified Structural Number Determined from Falling Weight Deflectometer Deflection Bowl Parameters and Its Proposed Use in a Benchmark Methodology

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Abstract: The structural capacities of various flexible pavements are often determined with the SNC (modified structural number) or SNP (adjusted structural number). The need for a non-destructive measurement technique, such as the FWD (falling weight deflectometer), had previously been explored to overcome the laborious test pit material characterization and layer thickness determination which had normally been needed to determine SNC or SNP. Lately, viable correlations were established between SNP/SNC and a variety of FWD deflection bowl measuring points or parameters. However, a large portion of the inherent structural information in the rest of the deflection bowl remains unused. The paper presents and validates relationship between effective structural number (SN_{eff} for pavement layers contribution) and for adjusted structural number (SNP_{eff}) and deflection bowl parameters utilizing the whole deflection bowl. The latter is inclusive of subgrade contribution. SNP is widely used to gather information on the structural integrity of the pavement system during preliminary network or project level investigations. A range of SNP_{eff} values are suggested for preliminary investigations using a benchmark methodology to help guide more efficient detailed investigations. However, using SNP_{eff} in this benchmark fashion cannot identify origin of the distress in a pavement system. The complementary use of deflection bowl parameter benchmark analysis can greatly enhance such investigations based on SNP_{eff} and identify origin of distress. In this paper, the use of SNP_{eff}, complemented with deflection bowl parameter benchmark analysis, is demonstrated with a case study.

Key words: SNC and SNP, flexible pavements, falling weight deflectometer, deflection bowl parameters, benchmark analysis.

1. Introduction

The SN (structural number) method is described as an index methodology and has found use and application world-wide through the AASHTO (American Association of State Highway Officials) design guide [1]. The origin of the empirical SN method is from the AASHO road tests in the late 1950s. In the mid-1970s, the TRRL (Transport and Roads Research Laboratory) defined the SNC (modified structural number), which includes the effect of the subgrade [2]. Typically, the well-known HDM (highway design and maintenance) Standards Model analysis tool [3, 4] makes use of the SNC and, more recently, the SNP (adjusted structural number) determined in various ways in their latest software, such as HDM-4 [5, 6]. SNC and SNP are often used interchangeably and, in this paper, SNP is preferred due to its specific reference to the use of the FWD (falling weight deflectometer) data in its determination.

In the original calculations of SNC, knowledge of detailed material and pavement layer thicknesses were required and resulted in laborious test pit and laboratory testing. Correlation attempts with the well-known Benkelman beam deflection followed to provide SNC determination from non-destructive structural response testing. The limitation of

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maximum deflection value only reflected to total pavement response and was contaminated with plastic deformations due to the measurement methodology resulted in SNC and Benkelman Beam deflection correlations with lower than required correlation coefficients for different types of flexible pavements [2]. Since the mid-1980s, the FWD has been taken over as the preferred non-destructive deflection measuring device with the advantage that it measured the whole deflection bowl and was resulted from dynamic or impact loading free of the Benkelman beam plastic deformation contamination [5, 7]. The HTRS (HDM-4 Technical Relationships Study) evaluated six available procedures to calculate SNP for inclusion of FWD measured deflections.

Based on the HTRS findings [1, 5, 7], Rohde's relationships were recommended if FWD and total pavement thickness data are available, whilst Jameson's formulae were recommended if only FWD data are available (therefore, no pavement layer thicknesses). Jameson's formulae used the maximum deflection and deflections at the 900-mm and 1,500-mm offsets to determine SNP [8, 9] and thereby making better use of the embedded structural response of the whole deflection bowl. Subsequently, Salt and Stevens [10] developed a correlation limited to the same three sensor deflections used in Jameson's formulae. Although this correlation was developed for granular pavements in New Zealand, an improved correlation was obtained and SNP was formulated as a single relationship inclusive of the subgrade component [10].

Evolution of relationships of structural number with deflections from Benkelman Beam to FWD as preferred deflection bowl measuring apparatus is partly due to the whole deflection bowl with significant inherent structural response information being able to be measured. However, this wealth of information can still largely be underutilized if only a single point (generally the maximum deflection) or only one additional point on the deflection bowl is used in the calculation of SNP values or other structural indices. The whole deflection bowl is also normally necessary for in-depth back-calculation of effective elastic moduli or stiffness of the various layers in order to do a detailed mechanistic analysis. The use of the whole deflection bowl is, however, promoted here as a benchmark methodology to help steer preliminary investigations at project or network level towards clearly identified areas with lesser structural strength or even obtain an initial indication of the origin of the distress.

An approximation of SNP determined via use of parameters on the whole deflection bowl (SNP_{eff}) is, therefore, explored and described in a benchmark or relative structural strength rating methodology. It is known that SNP, in general, can assist in distinguishing between weak and strong pavement structural conditions but cannot give exact origin of structural weakness [11]. Further use of deflection bowl benchmark analysis is, therefore, proposed to get to the cause of structural defect. The complementing use of SNP_{eff} with normal deflection bowl parameters in a benchmark methodology is recommended. The simple calculation of a number of slope deflection bowl parameters and their proven correlation with zones in the pavement structure of flexible pavements [7, 12-14] are well established, and world-wide application has been found [15, 16]. The complementary use of SNP_{eff} and deflection bowl parameter benchmark methodology is illustrated with a well-documented case study.

2. Background to SNP (Adjusted Structural Number) Determined with FWD (Falling Weight Deflectometer) Deflection Bowl Parameters

There have been numerous studies to find simple methods for calculating the SNP parameter or index using either destructive or non-destructive tests. The focus of this paper is on using the FWD as non-destructive testing device and to fully utilize the whole measured deflection bowl in order to overcome the need for any additional information, like layer thicknesses or detailed knowledge of material types and qualities. Layer thicknesses can be determined with some success via GPR (ground penetrating radar) readings with FWD surveys [17], additional coring, test pitting, other "hand holding" and personal interpretation. However, such an approach is rather laborious with limited guarantee of actual improved accuracy of the final structural evaluation outcome.

The 1993 AASHTO design guide recommends two methods to determine structural number from FWD NDT (non-destructive testing). NDT Method 1 has been used as a benchmark in SN correlation studies since it represents the original derivations of layer coefficients using back-calculation of elastic moduli based on mechanistic principles. The subgrade component of SNC is then calculated using the original relationship with CBR (California Bearing ratio) developed by the TRRL [8, 9].

The biggest problem with the first-generation methods has always seemed to stem from the original reliance on Benkelman beam deflections, which provided maximum deflection only. The rest of the deflection bowl with all the inherent pavement structural information was not used in such early correlation studies. In a number of cases, the correlations between Benkelman beam deflections and FWD were also found to be unreliable due to differences in measuring techniques and equipment. One of the major differences is due to the difference in measurement technique where Benkelman beam deflections also incorporate a plastic deformation component due to the slow reading and stationary departure from the measurement point.

It was found that methods using more points from the measured FWD deflection bowls of flexible pavements give good regression correlations [5]. It was also found that various methods tend to favor certain pavement types (e.g., stiff pavements or less stiff and more flexible pavements). Therefore, the later correlation study reported by Salt and Stevens [5] showed greater promise when well-documented New Zealand unbound granular pavements were used. This "local" SNP correlation was based on deflection points at 0, 900 mm and 1,500 mm of the measured FWD deflection bowl under standard 40 kN dropped weight. No layer thickness information is thus needed and only the description of a granular base flexible pavement is needed. The equation correlated (R^2 = 0.94) with the AASHTO NDT 1 Method derived SNP or SNC values and provided the following equation:

$$SNP_{nz} = 112(D_0)^{-0.5} + 47(D_0 - D_{900})^{-0.5} - 56(D_0 - D_{1,500})^{-0.5} - 0.4 \quad (1)$$

where:

SNP_{nz} is the SNP or SNC value determined for New Zealand unbound granular pavement;

D_0, D_{900} and $D_{1,500}$ are deflections in microns at offsets 0, 900 mm and 1,500 mm, respectively, under the standardized 40 kN FWD impact load.

The deflection bowl parameter benchmark methodology developed in South Africa [12-14] relies on the utilization of the full deflection bowl. This is used to benchmark or rate the structural capacity of the flexible pavement and related structural condition of zones of the pavement layers more effectively. This pointed the way towards possibilities to use the whole deflection bowl also in the possible determination of SNP_{eff} in a similar fashion.

A road with detailed layer thickness, material classification based on extensive test pit and laboratory testing and detailed FWD testing, was used by Schnoor and Horak [18] to correlate various of these deflection bowl parameters with SN, as determined by Rohde (SN_{Rhode}) [2, 8]. A number of these deflection bowl parameters correlated very well, individually with SN via a stepwise multiple regression procedure, where the deflection bowl was utilized more effectively with the following derived (R^2 = 0.98) regression equation:

$$SN_{eff} = e^{5.12} BLI^{0.31} A_{upp}^{-0.78} \quad (2)$$

where:

SN_{eff} is the effective SN at the time of measurement based on FWD deflection bowl parameters representing the structural layers excluding the subgrade contribution;

e is the natural logarithm;

BLI is the slope parameter determined by the difference between D_0 and D_{300} (see Eq. (5) below);

A_{upp} is also determined by simple spreadsheet calculation with the formula based on deflections measured at 0, 300, 600 and 900 mm, respectively (see Eq. (8)) [18].

However, SNP_{eff} was to be tested whether it is equal to or correlate with $SN_{Rhode} + SNSG = SNP_{Rhode}$. *SNSG* represents the subgrade component of this generalized structural number [8, 9]. *SNSG* can be determined by means of the well-published Eq. (3), which is shown below [2, 5, 8-10] for the CBR values of the actual subgrade material used in the detailed material and FWD data set [18]:

$$SNSG = 3.51(\log10\ CBR) - 0.85(\log10\ CBR)^2 - 1.43 \quad (3)$$

A reworking of the data [18] showed that $SNP_{eff} = SN_{eff} + 1.4$ (i.e., $SNSG = 1.4$) for this specific data set. In Fig. 1, the actual correlation thus determined for the Rhode relationship to calculate structural number inclusive of the subgrade structural number, SNP_{Rhode}, is shown versus SNP_{eff} determined for the original data set, which is described above [18]. It shows that, like for SN_{eff} versus SN_{Rhode}, SNP_{eff} has a very good correlation with SNP_{Rhode}.

The correlation shown in Fig. 1 clearly confirms that SN_{eff} and SNP_{eff} could be used interchangeably with SN_{Rhode} or SNP_{Rhode} when a benchmark or relative type evaluation methodology is used for pavement contribution and pavement plus subgrade response is included, respectively. This still did not mean that this relationship can be used on other flexible pavements as subgrade conditions are variable and may change drastically from uniform section to uniform section on a variety of roads. For this reason, SNP_{eff} was accepted as only an indicator value which lends itself to preliminary investigations via a benchmark methodology. Therefore, it was decided to see if SNP_{eff} could be correlated with the Eq. (1) carried by Salt and Stevens [5], which was shown before for similar pavement types and or other flexible pavement types. If possible, this will enable a broader use of the benchmark methodology using SNP_{eff}. This correlation study is described in the section to follow.

3. Correlation between SNP_{nz} and SNP_{eff} with Larger Flexible Pavement Database

Various well-documented databases with material information, layer thickness and detailed FWD surveys are available in South Africa to test this potential for correlation of SNP_{eff} with SNP_{NZ}. The original databases used by Maree and Bellekens [19] and the one developed by Hefer and Jooste [20] cover all flexible pavement types found in South Africa. This includes granular base pavements (with granular or deep granular support, as well as cemented subbase support), cement treated base pavements and asphalt base pavements. Of these flexible pavement types, the granular base pavements are the most common type of pavements used in South Africa. This, therefore, formed the basis of the first direct comparison and regression between the reported SNP_{nz} [5] as described in Eq. (1) and the SN_{eff} described in Eq. (2) [18]. Subsequently, SNP_{eff} and SNP_{NZ} were thus correlated for the various pavement types, using the above mentioned databases.

In Fig. 2, the correlation between SNP_{eff} and SNP_{nz} is shown for the combination of deep granular, granular base and granular subbases, as well as with cemented subbase support. In South Africa, such cement treated subbases are described as C3- or C4-quality material. Their typical UCS (unconfined compressive strength) ranges are, respectively, 0.75 MPa to 1.5 MPa and 1.5 MPa to 3 MPa. They are thus not strongly cemented and are mostly used as work platform to construct high quality granular bases

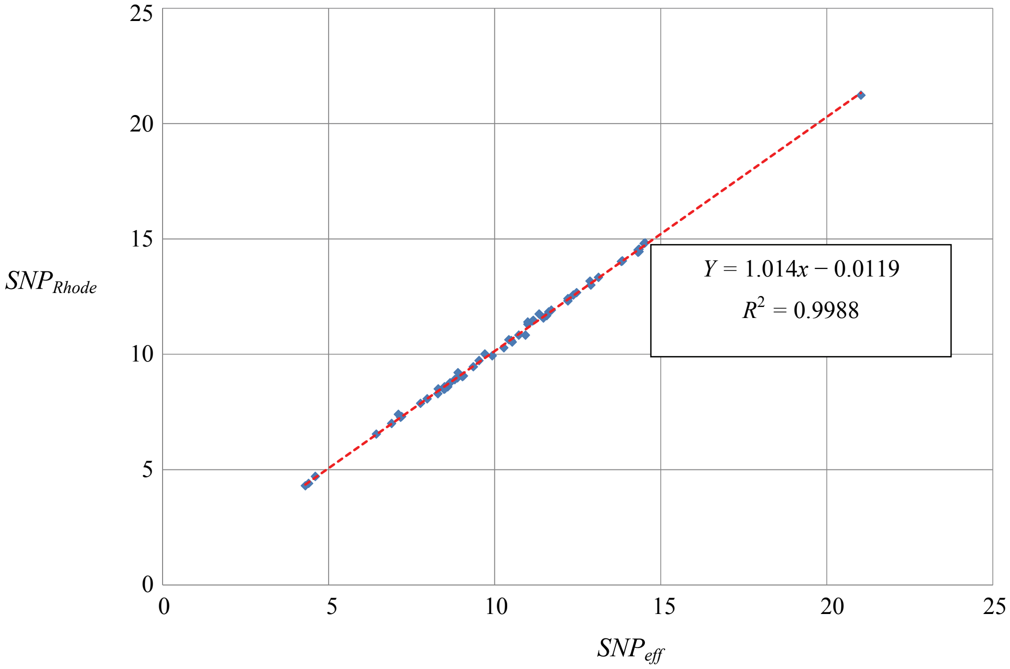

Fig. 1 FWD derived SNP Rhode versus SNP_{eff} with original Schnoor data set.

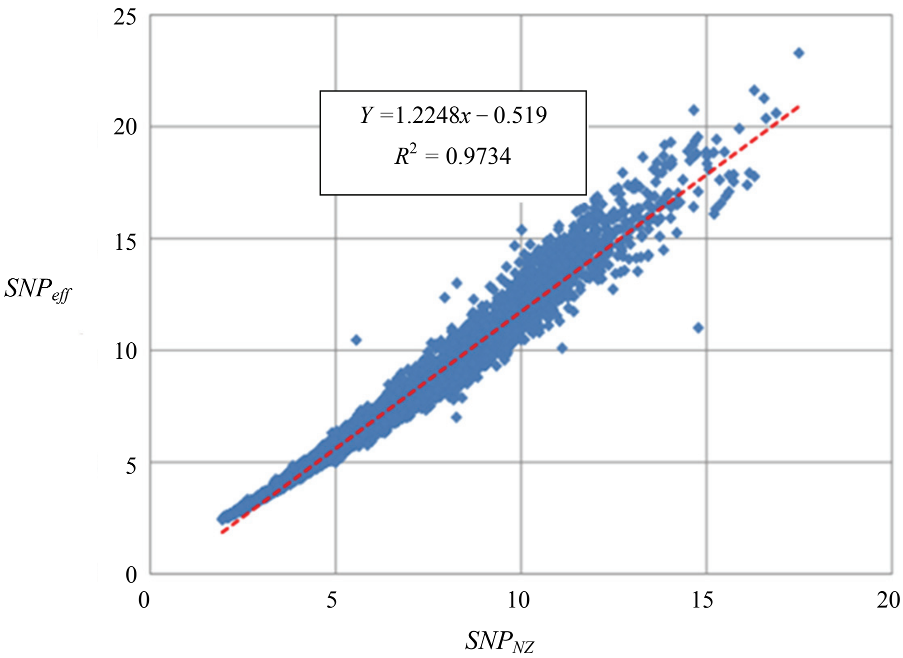

Fig. 2 All types of granular base pavement correlation between SNP_{eff} and SNP_{NZ}.

to a high density. These subbases are regarded as basically flexible in their behavior as their pre-crack life is less than 10% and the rest of the material behavior state is in a cracked or equivalent granular behavior state. It is not known if the New Zealand pavements contained cemented subbase support [5], but it can be assumed that they also classify the pavement as flexible. In Fig. 2, the combination of all granular type pavements shows a very positive correlation coefficient (R^2 = 0.97). As both correlation equations (SNP_{eff} and SNP_{NZ}) make use of the full deflection bowl, it is not really surprising that they correlate well. It does, however, show that, by using the full extent of the deflection bowl, a more robust statistical correlation can be derived.

This positive correlation also encouraged the correlation for other pavement types in the available databases. In Fig. 3, the correlations for asphalt base pavements are shown, and, in Fig. 4, the correlations for cemented base pavements are shown. The correlation coefficients for the asphalt and cemented base pavements are, respectively, R^2 = 0.93 and R^2 = 0.94, which is very good.

In Fig. 5, the correlation is shown for all combined flexible pavement types. It is significant that there is such a good correlation between SN_{eff} and SNP_{NZ} for all flexible pavement types. It can, therefore, be concluded that SNP_{eff} can also be calculated by Eq. (1) for all flexible pavement types found in South Africa. However, it should be stated that, in spite of the good correlations, it does not mean that such FWD deflection bowl determined SNP_{eff} or SNP_{NZ} should be seen as final definitive or accurate value of SNP. It rather should be treated as an indicative value which allows to be used in a relative comparison methodology as demonstrated with the benchmark methodology used with deflection bowl parameters.

4. Proposed Benchmark Analysis Methodology with SNP_{eff}

Benchmark methodology, as a preliminary investigative tool, had been developed and described for flexible roads and airports pavements and has recently been improved [8, 13, 14]. The detail of this benchmark methodology is not described here except to state that ranges for various deflection bowl parameters have been proposed based on the RAG (Red-Severe, Amber-Warning and Green-Sound) rating system.

Typically, in the original benchmark methodology, ranges of the particular slope deflection parameters, *BLI*, *MLI* and *LLI*, are used in a three-tiered condition rating system [8, 13, 14]. The *BLI* correlates well with the top 200 mm of a flexible pavement structure which typically includes the thin asphalt surfacing and typically 150-mm-thick granular base. The *MLI* correlates well with the middle layer or subbase structural response and the *LLI* correlates well with the lower layers (typically subgrade and selected layer combination). The radius of curvature (RoC_{200}) is

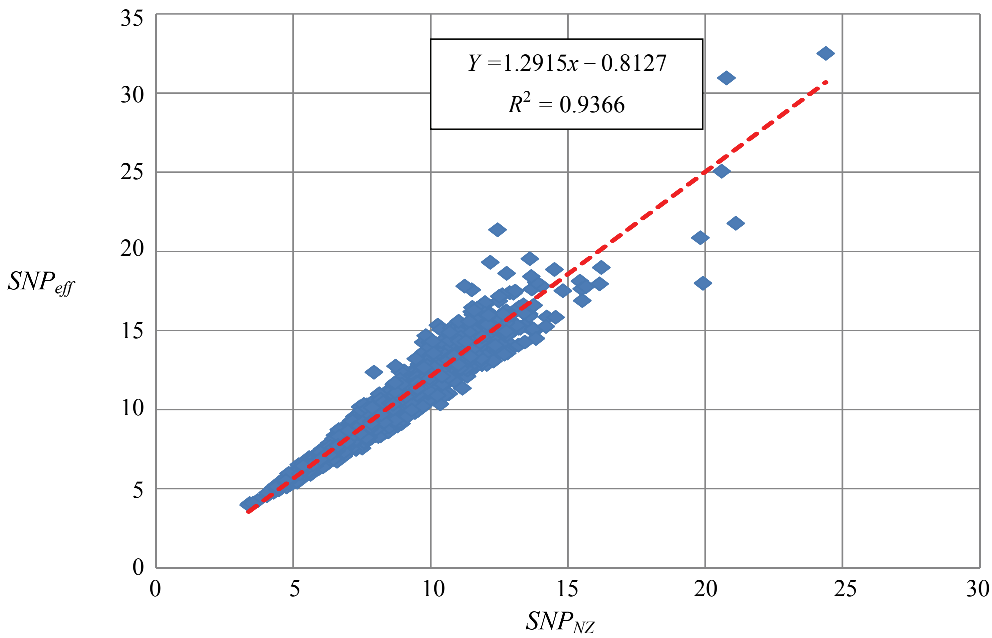

Fig. 3 All asphalt base pavements' correlations between SNP_{eff} and SNP_{NZ}.

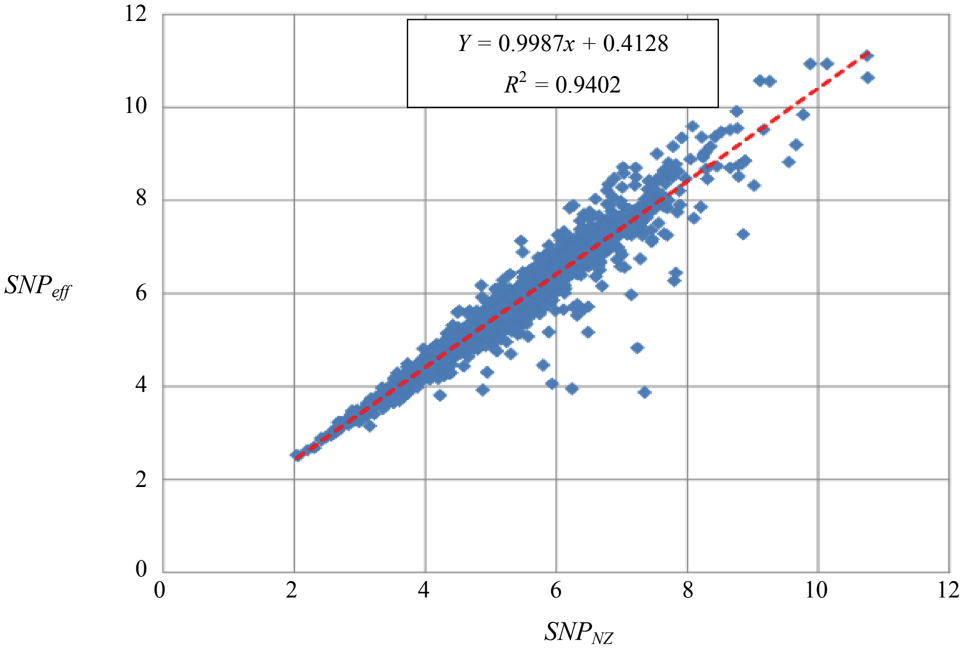

Fig. 4 All cemented base pavements' correlations between SNP_{eff} and SNP_{NZ}.

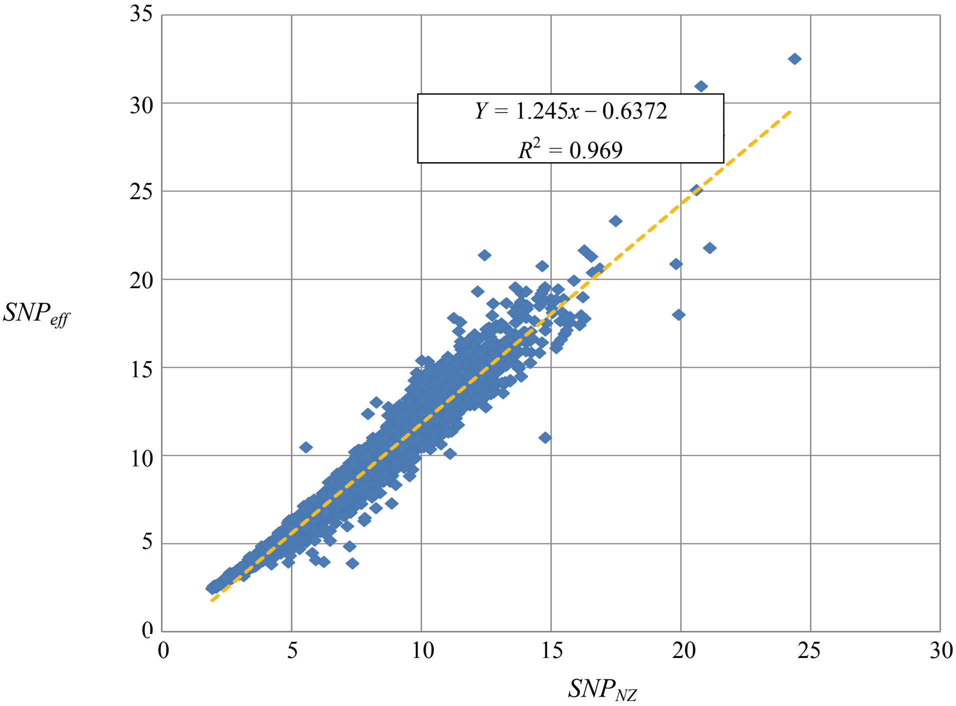

Fig. 5 All flexible pavements' correlations between SNP_{eff} and SNP_{NZ}.

often also used in conjunction with the *BLI* parameter as it tends to accurately reflect the structural response of the top 75-mm inclusive of the asphalt surfacing. Lately, the area parameters A_{upp} and AI_1 have also been correlated very well with *BLI* and the condition of the surfacing and top zone of the base layer [13, 14].

The equations for these simple to calculate deflection bowl parameters are as follows:

$$BLI = D_0 - D_{300} \quad (4)$$

$$MLI = D_{300} - D_{600} \quad (5)$$

$$LLI = D_{300} - D_{600} \quad (6)$$

$$RoC_{200} = L^2/(2D_0(D_0/D_{200} - 1)) \quad (7)$$

$$A_{upp} = (5D_0 - 2D_{300} - 2D_{600} - D_{900})/2 \quad (8)$$

$$AI_1 = (D_0 + D_{300})/2D_0 \quad (9)$$

where, D_0, D_{200}, D_{300}, D_{600} and D_{900} are deflections measured in micron at the corresponding offsets (0, 200, 300, 600 and 900 mm) from the point of maximum deflection D_0. The original L in *RoC* calculations is based on the original manual mechanical curvature meter with L = 127 mm (5 in.), which was fitted and measured between the dual tyres of a legally loaded truck as for Benkelman beam measurements [7, 13]. The FWD has a loading plate with radius of 150 mm which makes this original *RoC* calculation impossible. The closest next measuring point is at 200 mm and is used to calculate *RoC* associated with the FWD equipment, therefore, being described as RoC_{200} while L = 200 mm [7, 13].

The applied RAG ranges are shown in Table 1. It includes the suggested SNP_{eff} RAG ranges based on suggestions by Rhode and Hartman [9], Salt and Stevens [10], Horak et al. [14] and Pienaar et al. [21].

The use of SNP_{eff} in this suggested benchmark methodology is illustrated by using a well-documented road pavement where premature failure in the top of the high quality freshly crushed, continuously granular graded base and the 40-mm continuously grade asphalt surfacing with 20-mm UTFC (ultra-thin friction course) layers occurred. The rest of the pavement had a cement treated subbase and well-designed and constructed selected subgrade on good quality subgrade conditions. Detailed test pit and laboratory surveys were followed by back-analysis of effective elastic moduli, which confirmed the source of distress as originating from a combination of the top of base and surfacing. It was, therefore, explored to what level the benchmark analysis can confirm this analysis.

The standard 40 kN dropped weight FWD survey was done at 10-m intervals in the slow lane in both wheel paths, making it ideal for detailed survey analysis. In Fig. 6, the SNP_{eff} benchmark analysis based on the RAG ranges from Table 1 is shown for this granular base pavement. The RAG limits in Fig. 6 are indicated and are based on the guidance given by Zhang et al. [16] and shown in Table 1 [13, 14] purely to get an indication, of where potential structural problems may originate.

A detailed visual survey indicated distress in the form of crocodile cracking without any significant rut which confirmed this SNP_{eff} identified severely distressed spot in the LWP (left wheel path) while the RWP (right wheel path) did not show any visual distress. However, SNP_{eff} alone cannot indicate where in the pavement structure the distress in the pavement structure is originating from.

SNP_{eff} on its own is already a valuable structural index value, but Salt and Stevens [10] stated in confirmation: "Therefore, SNP is not able to give any indication of how a particular pavement structure would behave for a given layer configuration. For example, a road consisting of a stabilised base on top of inferior material may have a high SNP, but would in fact fail rather quickly due to cracking of the base layer."

Thus SNP_{eff} derived from FWD deflection data needs to be complemented by the FWD deflection bowl parameters benchmark methodology [7, 12, 14] to help identify specific areas and zones of structural layers where structural condition or distress can be identified. The FWD (40 kN) derived maximum deflection in Fig. 7 illustrates that no structural problem can be detected by using maximum deflection

Table 1 Benchmark ranges for 566 kPa contact stress (40 kN) on a granular base pavement.

Structural condition rating	Deflection bowl parameter benchmark analysis ranges					
	RoC (m)	Max deflection (μm)	*BLI* (μm)	*MLI* (μm)	*LLI* (μm)	SNP_{eff}
Sound	> 100	< 500	< 200	< 100	< 50	> 6
Warning	50~100	500~750	200~400	100~200	50~100	4~6
Severe	< 50	> 750	> 400	> 200	> 100	< 4

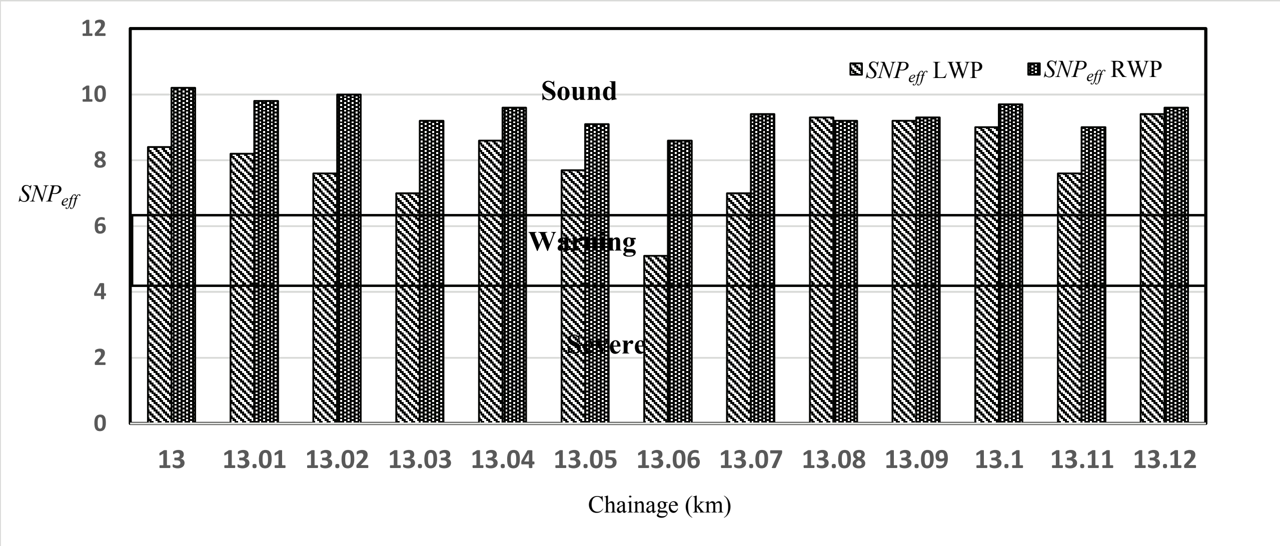

Fig. 6 ***SNP_{eff}*** **benchmark analysis on a granular base pavement.**

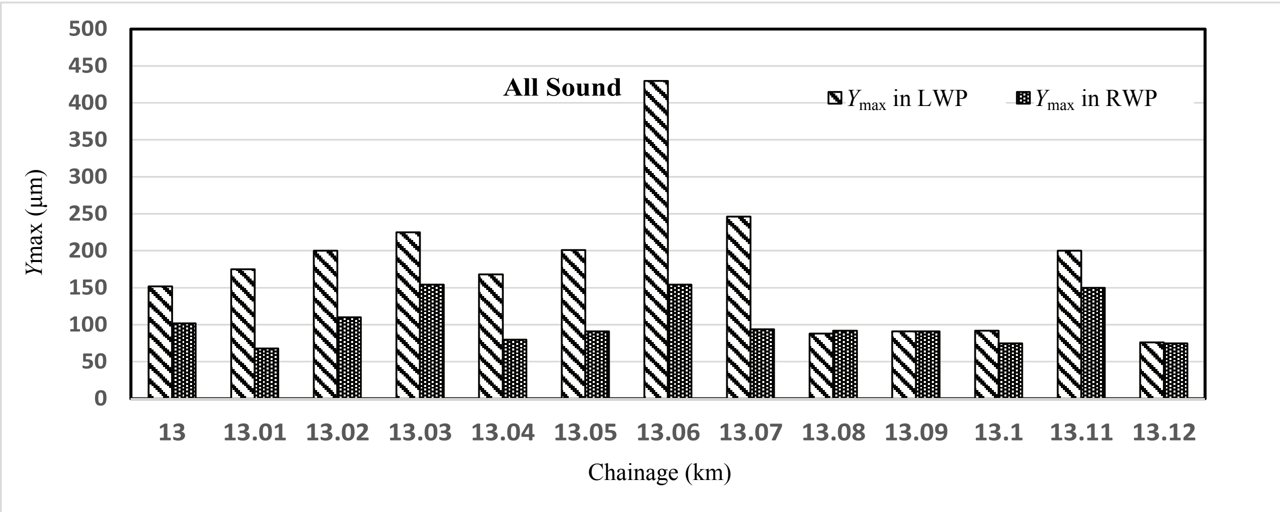

Fig. 7 Maximum deflection benchmark analysis for a distressed road section.

alone based on the RAG benchmark system. The spot where maximum deflection occurs is larger than the rest, but it still does not show up as being in a warning or severe condition. This serves to show that maximum deflection is less sensitive to structural strength evaluation than even SNP_{eff}, as it did not even pick up the visually distressed area identified by SNP_{eff}. *LLI* and *MLI* benchmark analysis (not shown) confirmed the detailed back analysis and test pit observations that no structural deficiencies occurred in these lower structural support layers. In Fig. 8, the *BLI* benchmark analysis is shown. The visually confirmed distressed spot is correctly identified, indicating that the base and surfacing combination or zone is in a warning condition. This spot coincides with the spot identified in a warning condition by the SNP_{eff} benchmark analysis.

No further spots in warning were identified with the *BLI* benchmark analysis. A further analysis with RoC_{200} shown in Fig. 9 enabled a more detailed analysis of the nature of the origin of distress. This RoC_{200} benchmark analysis was able to identify areas where the severe RoC_{200} coincided with identified visual surveyed severe conditions confirming premature distress in the asphalt surfacing and the top of the crushed stone base. Over and above the spot

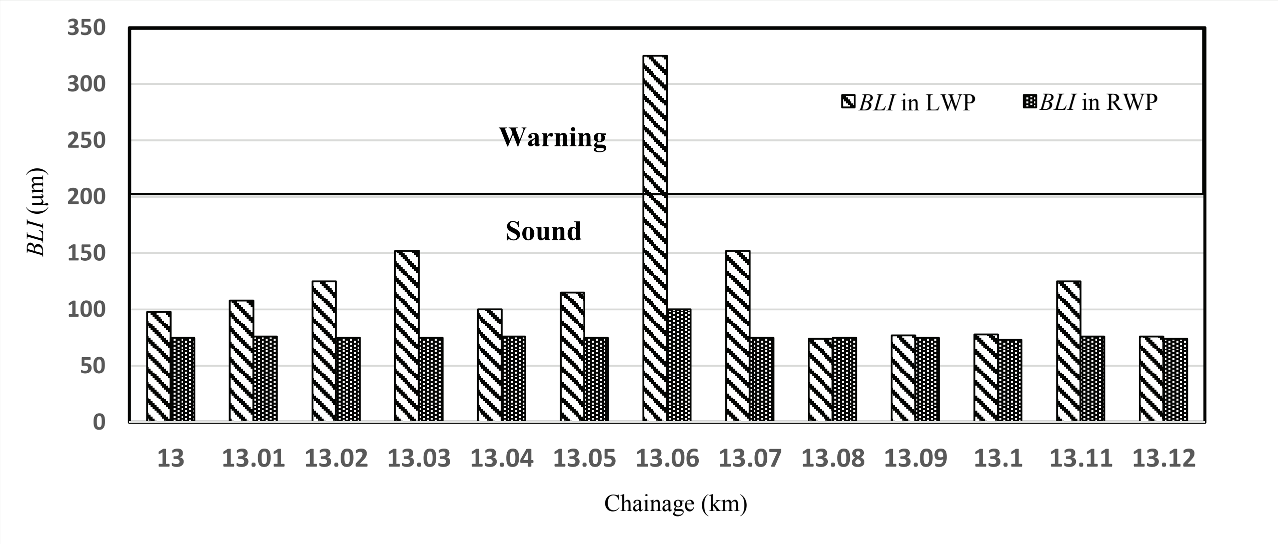

Fig. 8 ***BLI* benchmarking analysis to identify origin of distress.**

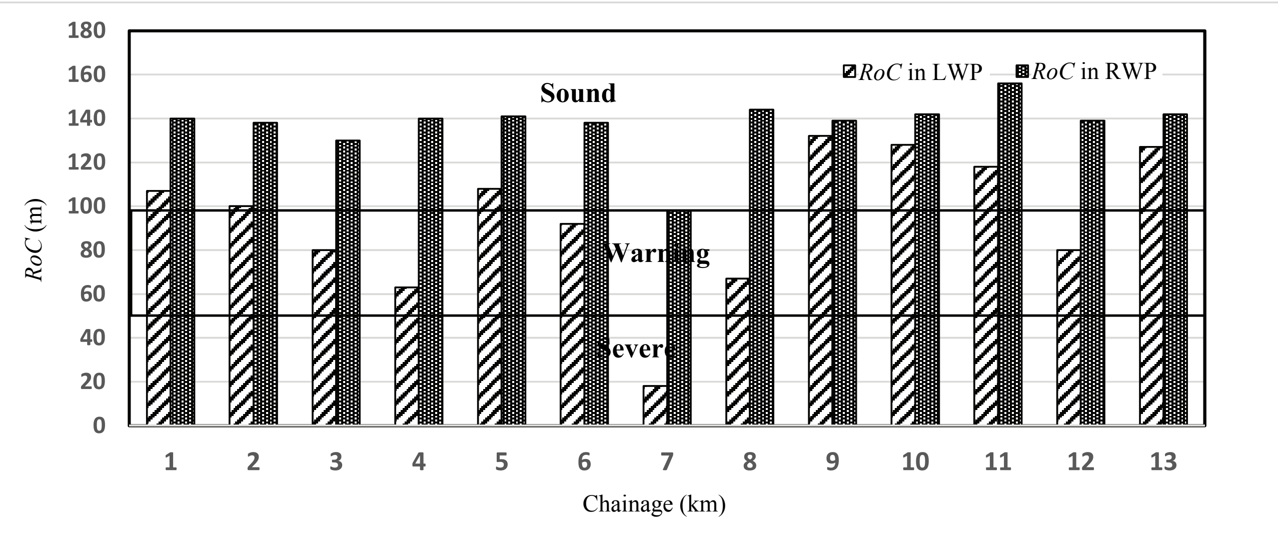

Fig. 9 ***RoC_{200}* benchmark analysis for short distressed road section.**

visibly in a severe condition, other potential problems in a warning condition also in the left wheel track could now be observed. Of significance is the fact that the right wheel track, next to the identified severe spot in the left wheel track, also now shows potential problems signaling RoC_{200} values close to or in the warning condition.

This is significant as this RWP section did not initially show distress in the form of premature crocodile cracking. After more traffic exposure and subsequent rain exposure, the visible distress did in fact appear at these spots as well. The RoC_{200} parameter, therefore, was able to show potential for distress in progress as the interface zone between the asphalt surface and the top of the base layer.

The mechanism of distress was identified as water infiltration via a porous asphalt surfacing after seasonal rain. Highly channelized traffic caused water accumulation at the top of base and underside of the asphalt surfacing to be exposed to EPWP (excessive pore water pressure). This EPWP thus caused growth of the asphalt surface de-bonding in the longitudinal, as well as transverse directions. This de-bonding could also be confirmed by listening to the differential hollow sound when tapped with a hammer. This potential for cracking extended up to 1 m from the original area of distress in the wheel path. Cracking on de-bonded areas only showed up much later after additional seasonal rain, but growth was limited after removal of restrictive traffic accommodation measures (lane closures with highly channelized traffic) to normal traffic flow coinciding also with a shifted transverse normal distribution wheel path.

This type of distress and forensic analyses had been reported in more detail elsewhere [22]. In all such cases, the use of benchmark technology with SNP_{eff} or other structural indices derived from FWD deflection bowls have been shown to be good in first level or a preliminary investigation tool. For origin of distress, it had shown that slope deflection bowl parameters and radius of curvature (RoC_{200}) can provide additional insight into possible origin of distress in the upper region of the pavement structural system. This had been found to be useful in directing more efficient detailed traditional testing, sampling and laboratory testing or back-calculating effective elastic moduli for detailed mechanistic structural analyses.

5. Conclusions

SNP can be derived from FWD deflection bowl information as an approximation of the SNP values, which are normally derived from detailed material and layer thickness information.

A large database of South African flexible pavements was used to successfully correlate the SNP_{NZ} with SNP_{eff}. This holds true not only for granular base pavements but also for asphalt base and cemented base pavements. The good correlations are testimony to the improved value provided by a better utilization of the inherent structural response information imbedded in the full deflection bowl.

SNP_{eff} derived from deflection bowl parameters representing deflections up to 900 mm from the point of maximum deflection and inclusion of the CBR based subgrade structural number were proved to give good correlation with previously published SNP values determined using pavement thickness and two deflection points as developed by Rhode. The latter was used as the reference SNP in this regression analysis. A similar SNP_{NZ} regression analysis with unbound granular pavements in New Zealand, which made use of deflection at points 0, 900 and 1,500 mm from the point of maximum deflection, correlated very well with the above mentioned SNP_{eff}.

SNP_{eff} should be ideally used in a benchmark methodology in preliminary investigation phases. As illustrated via a specific case study, SNP_{eff} can identify a distressed section or spot but cannot identify origin of distress in depth of the pavement structure.

It is recommended that SNP_{eff} should be complemented with the well-known deflection bowl parameter structural benchmark methodology. These deflection bowl parameter values which are simple to be calculated via mostly slope parameters provide for a three-tiered relative structural condition rating ("sound", "warning" and "severe" structural relative condition). Various zones and combinations of layers can thus be identified which may be the origin of distress.

No further detailed analyses, like structural life predictions, are done here as these benchmark analyses methods are to be used as preliminary screening tools to help guide more detailed investigations and analyses. This approach has obvious application at network level PMS (pavement management system) analyses, as well as preliminary investigation at project level investigations of flexible pavements.

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