Structural number determined with the falling weight deflectometer and used as benchmark methodology

Emile Horak¹, Arno Hefer² James Maina³ and Steve Emery⁴
1. Kubu Consultancy Pty Ltd, Centurion, South Africa
2. Arno Hefer Consulting CC, Pretoria, South Africa
3. University of Pretoria, Department of Civil Engineering, Pretoria, South Africa
4. Kubu Australia Pty Ltd, Perth, Australia

E-mail: emileh@global.co.za

Abstract: The modified or adjusted structural number (SNC or SNP) is widely used to define the structural capacities of various flexible pavements. Viable correlations between either SNP or SNC and a variety of falling weight deflectometer (FWD) deflection bowl measuring points or parameters exist. Whilst historic use of maximum deflection continues, a large portion of the inherent structural information in the rest of the deflection bowl goes underutilised. The paper presents and validates a single relationship of parameters, representing the full deflection bowl, and effective adjusted structural number (SNP\textsubscript{eff}). SNP and the structural condition index (SCI) are widely used on network and preliminary project level investigations, but cannot identify origin of the distresses. The complementary use of a deflection bowl parameter benchmark analysis can greatly enhance such investigations. In this paper the use of deflection bowl derived SNP\textsubscript{eff}, SCI complemented with deflection bowl parameter benchmark analysis is demonstrated with a case study.

Keywords: Modified and Adjusted Structural Number, flexible pavements, falling weight deflectometer, deflection bowl parameters, benchmark analysis, structural condition index.

1. Introduction

The origin of the empirical structural number (SN) method is from the American Association of State Highway Officials (AASHO) road tests in the late 1950’s. The SN method is described as an index methodology and has found use and application world-wide through the AASHTO design guide [0]. In the mid 1970’s the Transport and Roads Research Laboratory (TRRL) defined the modified structural number (SNC), which includes the effect of the subgrade [2]. Typically the well known Highway Design and Maintenance Standards Model (HDM) analysis tool [2, 3] makes use of modified structural number (SNC), and more recently the adjusted structural number (SNP) 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.

In the original calculations of SNC, knowledge of detailed material and pavement layer thicknesses was required and correlation attempts with the well known Benkelman beam deflection followed only to show that SNC and Benkelman Beam deflection are not directly interchangeable [2]. The falling weight deflectometer (FWD) has taken over as the preferred non-destructive deflection measuring device for various reasons [5, 7]. The HDM-4 Technical Relationships Study (HTRS) on inclusion of FWD measured deflections into the Model evaluated six available procedures to calculate SNC. Based on the analysis, Rohde’s relationships were recommended if FWD data and total pavement thickness data are available, whilst Jameson’s formulae were recommended if only FWD data is available. Jameson’s formulae use maximum deflection and deflections at the 900 mm and 1500 mm offsets to determine the SNP components [8, 9]. 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 illustrates that the whole deflection bowl has significant inherent structural response information. This wealth of information is largely under-utilized 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.
A detailed correlation study was done on a flexible pavement in South Africa with very detailed FWD survey and material test pit information [11] to expand the use of the full deflection bowl and overcome the need for knowledge of pavement or layer thicknesses in the determination of SNP. The Rohde deflection based method of SNP determination was used as reference due to the availability of reliable pavement thickness data, the outcome of the HTRS Study [8] and its perceived correctness by other researchers [10]. SNP was thus correlated with a variety of deflection bowl parameters, which utilised the deflection bowl more effectively over the whole deflection bowl width [11]. This correlation relationship, specific for South African flexible pavements, provided a non-destructive method to determine the effective structural number (SNP_{eff}) of the pavement structure as it is an SNP value representing the conditions at the time of FWD measurement. In the correlations presented subsequently, the work done by Salt and Stevens [10] on a dataset of pavements in New Zealand is revisited. This derived SNP is called SNP_{nz} to distinguish it from SNP_{eff}, described above. In this paper the correlation of SNP_{nz} with SNP_{eff} is shown and evaluated for either of them to be used with other flexible pavement types as well. For South Africa, a large database of various types of flexible pavements (granular, asphalt and cement base pavements) [12] was used in this correlation study.

The designed SNP value or required SN value (SNP_{req}) can also be determined from un-trafficked road sections (e.g. shoulder or between wheel paths) or as-built information. This is demonstrated with a database originally used in the development of the deflection bowl parameter benchmark methodology [13]. The ratio of SNP_{eff} to SNP_{req} provides the possibility to determine a structural condition index (SCI). SCI is used as screening tool for decisions regarding maintenance and rehabilitation in pavement management systems worldwide [14, 15, 16]. It is known that SNP_{eff} and therefore also SCI thus calculated from deflection parameters can assist in distinguishing between weak and strong pavement structural conditions, but cannot give exact origin of structural weakness [17]. 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 slope deflection bowl parameters and their proven correlation with zones in the pavement structure of flexible pavements [7, 18] are well established and has found application world-wide [15, 16]. The complementing use of SNP_{eff}, SCI and deflection bowl parameter benchmark methodology is illustrated with a case study.

2. Background to SNP determined with FWD 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. In this case the focus 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 thickness or in detail knowledge of material types and qualities. Layer thicknesses can be determined with some success via ground penetrating radar (GPR) readings with FWD surveys [14], but normally with a need for additional “hand holding” and personal interpretation. This makes such an approach 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 non-destructive testing (NDT). 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 developed by the TRRL [8, 9].

The biggest problem with the first generation methods have 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 tended to be ignored in such early correlation studies. In a number of cases the correlations between Benkelman beam deflections with FWD were also found to be unreliable due to differences in measurement technique and equipment. It was found that methods using more deflection points on the measured FWD deflection bowls of flexible pavements give good regression correlations [5]. It was also found that various methods tend to favour certain pavement types (e.g. stiff pavements or less stiff, 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, 900mm and 1500mm of the measured FWD deflection bowl under standard 40kN dropped weight. The equation correlated (R^2 = 0.94) with the AASHTO NDT 1 method derived SNP or SNC values and provided the following equation:

\[
\text{SNP}_{nz} = 112(D_0^{0.5} + 47(D_0 - D_{900})^{0.5} - 56(D_0 - D_{1500})^{0.5} - 0.4
\]

(1)
Where SNP$_{nz}$ is the SNP or SNC value determined for New Zealand unbound granular pavements and D$_0$, D$_{900}$ and D$_{1500}$ are deflections in microns at offsets 0, 900 and 1500 mm, respectively, under the standardised 40kN FWD impact load.

The deflection bowl parameter benchmark methodology developed in South Africa [19] relies on the full utilization of the deflection bowl to benchmark or rate the structural capacity of the flexible pavement and structural condition of zones of the pavement layers more effectively. 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 [11] to correlate various of these deflection bowl parameters with SNP as determined by Rohde [2, 8]. A number of these deflection bowl parameters correlated very well individually with SNP via a stepwise multiple regression procedure, where the deflection bowl was utilised more effectively with the following derived ($R^2 = 0.98$) regression equation;

\[ 
\text{SNP}_{\text{eff}} = e^{5.12 \times \text{BLI}^{0.31} \times \text{Aupp}^{-0.78}} 
\]

Where SNP$_{\text{eff}}$ is the effective SNP at the time of measurement based on FWD deflection bowl parameters, $e$ is the natural logarithm, BLI is the slope parameter determined by the difference between D$_0$ and D$_{300}$ (see equation 4 below). Aupp is also determined by simple spreadsheet calculation with the formula based on deflections measured at 0, 300, 600 and 900mm respectively (see equation 8) [11].

3. Correlation between SNP$_{nz}$ and SNP$_{\text{eff}}$ with larger flexible pavement data base

The original database used by Maree and Bellekens [13] and the one developed by Hefer and Jooste [12] 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 base pavements and asphalt base pavements. Of these flexible pavement types, the granular base pavements are the most common type of pavement 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 equation (1) and the SNP$_{\text{eff}}$ described in equation (2).

In Figure 1, the correlation between SNP$_{\text{eff}}$ and SNP$_{nz}$ are shown for both deep granular, granular base with cemented subbase support. It is not known if the New Zealand pavements contained cemented subbase support [5]. In both types of subbase support the correlation shown is very good ($R^2$ from 0.97 to 0.99). In Figure 2 the combination of all granular type pavements are shown with very positive correlation coefficient ($R^2 = 0.97$). As both correlation equations 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 encouraged the correlation for other pavement types also in the data bases available. In Figure 3, the correlation for asphalt base pavements is shown and in Figure 4 the correlations for cemented base pavements are shown. The correlation coefficients for the asphalt and cemented base pavements are respectively $R^2 = 0.94$ and $R^2 = 0.93$, which is still very good.

It is significant that there is such a good correlation between SNP$_{\text{eff}}$ and SNP$_{nz}$ for all flexible pavement types separately. In Figure 5 the correlation is shown for all flexible pavement types. This implies that either SNP$_{nz}$ or SNP$_{\text{eff}}$ can be used with confidence to determine a SNP value for all flexible pavement types.

4. Structural Condition Index calculations from SNP$_{\text{eff}}$

FWD surveys form the basis of most structural evaluation procedures by a variety of road authorities on a project level as well as in pavement management systems (PMSs) on the network level and the use of structural indices features strongly in these PMSs [15]. A good application of this approach is by the Texas DOT (TxDOT) in their Pavement Management Information System (PMIS). TxDOT developed FWD-based structural condition estimators, using primarily SNP and the Structural Condition Index (SCI) as screening tools in their PMIS for decisions regarding maintenance and rehabilitation.

The SCI is determined as follows

\[ \text{SCI} = \frac{\text{SNP}_{\text{eff}}}{\text{SNP}_{\text{req}}} \]  

Where;
SCI = Structural Condition Index
SNP_{eff} = existing Structural Number
SNP_{req} = required Structural Number typically calculated as needed for the next 20 years based on known material qualities and thicknesses.

Zhang et al. [16] states: 'Because of the simplicity of the SCI, the interpretation of its meaning is straightforward. An SCI greater than one would indicate a sound pavement structure while SCI less than one means the pavement is no longer structurally adequate.' It is therefore possible to use SCI in a three-tier benchmark condition rating system similar to the deflection bowl benchmark methodology [7]. In this case the sound or green colour is associated with SCI above 1, warning or amber colour is associated with SCI between 1 and 0.75 and severe or red condition is associated with SCI values below 0.75. This is often referred to as the RAG condition rating system. Even though the use of SCI on a network level in a PMS where detailed layer thicknesses are not known has considerable value, SCI can also not give more information or help to identify origin of distress if identified with SCI.

y = 1.0586x + 0.2389
R^2 = 0.9877

Figure 1. Granular base pavement correlation between SNP_{eff} and SNP_{NZ} for different support conditions

SNP_{eff} = 1.0586 SNP_{N} + 0.2389, R^2 = 0.99

SNP_{eff} = 1.2461 SNP_{NZ} - 0.6692, R^2 = 0.97

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

SNP_{eff} = 1.2915 SNP_{N} - 0.8127, R^2 = 0.9366

Figure 3. All asphalt base pavement correlation between SNP_{eff} and SNP_{NZ}
The original dataset used by Maree and Jooste [20] was analysed to illustrate how SCI can monitor the structural strengthening due to an asphalt overlay. In this case SCI could be derived by using an un-trafficked shoulder survey to derive $SN_{\text{req}}$ while $SN_{\text{eff}}$ could be derived from the outer wheel track (OWT) FWD survey at the same position. The after overlay was derived in the same fashion and the before overlay SCI values are shown in Figure 6. The structural benefit due to the overlay provided showed improved SCI in all cases to be larger than 1 which is the sound condition as indicated by the colour line. As shown the before overlay had spots where the SCI was in the warning condition falling between the green and amber lines.

5. SCI Benchmark analysis complementing

$SN_{\text{eff}}$ on its own is already a valuable structural index value, but Salt and Stevens [10] states “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.” Therefore, SNP and SCI benchmark analyses thus derived should be complemented by another reference value or benchmark methodology which can help identify origin of distress in a flexible pavement.

Thus $SN_{\text{eff}}$ and or SCI derived from FWD deflection bowl survey information need to be complemented by the FWD deflection bowl parameters benchmark methodology [7, 18] to help identify specific area and zones of structural layers where structural condition or distress can be identified. The latter methodology is not described in detail here except to state that ranges of particularly the slope deflection parameters BLI, MLI and LLI in a
three tiered condition rating system are used as described above for SCI. The radius of curvature (RoC200) is often also used in conjunction with the BLI parameter. Lately the area parameters A_upp and AI1 have also been correlated very well with BLI and the condition of the surfacing and top zone of the base layer [21]. The equations for these simple to calculate deflection bowl parameters are as follows;

\[
\begin{align*}
\text{BLI} &= D_0 - D_{300} \\
\text{MLI} &= D_{300} - D_{600} \\
\text{LLI} &= D_{300} - D_{600} \\
\text{RoC}_{200} &= \frac{L^2}{(2D_0(D_0/D_{200} - 1))} \\
\text{A}_{\text{upp}} &= \frac{(5D_0 - 2D_{300} - 2D_{600} - D_{900})}{2} \\
\text{AI}_1 &= \frac{(D_0 + D_{300})}{2D_0}
\end{align*}
\]

Where \(D_0, D_{200}, D_{300}, D_{600} \text{ and } D_{900}\) are deflections measured in micron at the corresponding offsets (0, 200, 300, 600 and 900mm) from the point of maximum deflection \(D_0\). The original \(L\) in RoC calculations described by Dehlen was 127mm, but for FWD measurements it is for an \(L=200\)mm [7].

The use of such an improved SNP_eff derived from deflection bowl to calculate SCI 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 40mm continuously grade asphalt surfacing with 20mm ultra-thin friction course (UTFC) 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. Benchmark analyses with parameters LLI and MLI (not shown) also confirmed a sound subbase and subgrade condition.

The standard 40kN dropped weight FWD survey was done at 10m intervals in the slow lane in both wheel paths making it ideal for detailed survey analysis. In Figure 7 the FWD (40kN) maximum deflection is shown and via the RAG benchmark system illustrates that no structural problem can be detected by using maximum deflection alone. 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.

The designed SNP_req could be calculated accurately as SNP_req = 8 (with inclusion of the subgrade contribution) as material properties and layer thicknesses were well documented. SNP_eff could be determined from equation (2) using deflection bowl parameters. Therefore, SCI as per equation (3) could be calculated with confidence. In Figure 8, the SCI benchmark analysis for the same stretch of road is shown. The RAG limits in Figure 8 are indicated and are based on the guidance given by Zhang et al. [16] purely to get an indication of where potential structural problems may originate and described above. As can be seen it is in the left wheel track that distress can be observed while the right wheel track showed no visual distress yet is confirmed by the SCI values in the right wheel track also shown.

Detailed visual survey indicating distress in the form of crocodile cracking without any significant rut confirms this SCI-identified distressed spot. This is already a much better indication of distress and pending distress than what maximum deflection could indicate. Even though areas with possible distress were identified, it was confirmed that SCI cannot indicate where in the pavement structure the problem may originate. Further deflection bowl benchmark analysis was thus needed to identify the origin of distress.

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 Figure 9, the BLI benchmark analysis is shown. The visually confirmed distressed spot is now identified indicating the base and surfacing combination or zone is in a warning condition. This spot coincides with the spot identified in a severe condition by the SCI benchmark analysis.
No further spots in warning were identified with the BLI benchmark analysis. A further analysis with RoC\textsubscript{200} shown in Figure 10 enabled a more detailed analysis. This RoC\textsubscript{200} benchmark analysis was able to identify areas where the severe RoC\textsubscript{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 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\textsubscript{200} values in the warning condition.
In Figure 11, the dimensionless $A_{I1}$ deflection area parameter was also calculated for the same section and wheel paths. A straight correlation from the BLI condition ratings [21] was used to impose the RAG criteria for $A_{I1}$ as well. It shows that $A_{I1}$ may in fact be even more sensitive to the top of base and surfacing structural condition than any of the other parameters. All the spots identified by RoC also showed up except it now shows two more spots already in severe condition. This conclusion was subsequently confirmed by actual distress occurrence in the form of crocodile cracking which tended to appear in a very short time in the areas thus identified by the $A_{I1}$ parameter. In this case the faintly cracked asphalt surface could not be identified initially by visual inspection, but after rain and moisture ingress into the top of the base this form of distress occurred virtually overnight.

6. Conclusions
Adjusted Structural Number (SNP) can be derived from FWD deflection bowl information as an approximation of the SNP values normally derived from detailed material and layer thickness information. SNP\textsubscript{eff} derived from only two deflection bowl parameters representing deflections up to 900mm from the point of maximum deflection proved to give good correlation with the SNP values derived with pavement thickness and two deflection points. The latter was used as the reference SNP in this regression analysis. A similar SNP\textsubscript{NZ} regression analysis with unbound granular pavements in New Zealand, which made use of deflection at points 0, 900 and 1500mm from the point of maximum deflection, correlated very well with the above mentioned of SNP.

A large database of South African flexible pavements was used to correlate successfully the SNP\textsubscript{NZ} with SNP\textsubscript{eff} not only for granular pavements, but also for asphalt base and cemented base pavements. The good correlation is a testimony to the value of better utilization of the full deflection bowl with inherent structural response information.

Structural Condition Index (SCI) values can be calculated via SNP\textsubscript{eff} and SNP as for design or as required (SNP\textsubscript{req}). This indicator can also be used in a benchmark method. As illustrated via a specific case study, neither SCI nor SNP\textsubscript{eff} can go beyond identification of a distressed section or spot. On their own, they cannot identify origin of distress in depth of the pavement structure.

It is recommended that SNP\textsubscript{eff} and SCI be complemented with the well known deflection bowl parameter structural benchmark methodology. These simple to calculate mostly slope parameters, radius of curvature and various area parameter deflection values at pre-set offsets from the point of maximum deflection provide for a three tiered condition rating. Various zones and combinations of layers can thus be identified which may be the origin of distress also identified by means of the SCI and SNP\textsubscript{eff} indices.

No further detailed analyses is done like structural life predictions here as these benchmark analyses methods are to be used as preliminary screening tools to help guide more detailed investigations and analyses.

7. References


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