Journal of Civil Engineering and Architecture 17 (2023) 192-198
doi: 10.17265/1934-7359/2023.04.004

Considerations of Area Parameter of the Deflection Basin on the Structural Evaluation of Flexible Pavements

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Abstract: By using the concept of modified structural number (SNC) and deflection measurements, a simplified calculation methodology, that permits the structural condition evaluation of an existing pavement, is being proposed. The values of SNC and the curvature parameters were first determined through simulations using the ELSYM-5 software. Deflection measurements were carried out in experimental segments of Brazilian highways. The resilient moduli of each layer were determined from backcalculation using the ELMOD program for a three-layer system. Theoretical correlation models between SNC and the basin deformation parameter were determined and later, calibrated with the results of experimental sections. Utilizing the studied models, a good correlation was found between SNC, area parameter and maximum deflection, enabling the determination of SNC through deflection measurements and assisting in the diagnostic of structural condition of asphalt pavements.

Key words: Structural evaluation, SNC, deflection basin, FWD.

1. Introduction

Since the mid-1980s, in Brazil, the Falling Weight Deflectometer – FWD is used as a well-established and valuable non-destructive testing (NDT) device for evaluating the structural capacity of pavements in service for rehabilitation designs. The advantages of this type of equipment in relation to the traditional Benkelman beam are speed and security of execution in the field work, reliability of results as the repeatability and, mainly, the ability to measure the whole shape of deflection basins.

With the data of existing pavement thickness and deflection measurements by geophones, located in fixed line and distance to the plate center, it is possible to estimate from backcalculation the theoretical modulus of materials properties of the evaluated pavement structure.

Despite of the wide availability of software, the structural diagnostic of the pavement through backcalculation demands a hard-working process and is not commonly used, once the results of deflection measurements of the complete basin, even being valuable results, they are, in the most part of time, neglected.

This paper intends to show a simplified calculation methodology that permits the evaluation of the existing pavement structure, using the concept of modified structural number (SNC) and some deflection basin parameters (DBP), as maximum deflection (D_0), the deflection at the distance of 120cm (D_{120}) and the area parameter, among others.

The values of SNC, used to characterize the condition of existing pavement were correlated theoretically with the curvature parameters (A, R, SCI, BDI, BCI, D_0 e D_{120}) and calibrated in field using the results of inventory accomplished in an experimental segment of flexible asphalt pavement in service in Brazil, representing a case of elastic of three layers system. The structures used in the theoretical study

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were characterized through simulations using the software ELSYM-5.

2. Structural Parameters

2.1 Structural Number

The structural number (SN), according to Refs. [1-7], is a parameter used to characterize the load-carrying structural capacity of pavement, and it is represented by the following equation (1).

$$SN = 0{,}0394\sum_{i=1}^{n} a_i \cdot h_i \qquad (1)$$

Where: ai = Structural layer coefficient of the i_{th} layer of the pavement, function of the material resilient modulus;

hi = Thickness of i_{th} pavement layer (mm).

The AASHTO Road Test was constructed on a single uniform subgrade therefore the effect of different subgrades could not be estimated and structural number could not include a subgrade contribution. Pavements of a particular structural number but built on different subgrades will therefore not carry the same traffic to a given terminal condition.

In order to consider the different values of subgrade support and to generalize the founded models for other bearing conditions of foundations, it was suggested by [8] apud [9] the concept of modified structural number (SNC), calculated using the equation (2) follow presented:

$$SNC = SN + 3{,}51 \cdot \log(CBR) - 0{,}85 \cdot (\log(CBR))^2 - 1{,}43 \qquad (2)$$

Where: SN = Structural number;

CBR = California Bearing Ratio, assumed as CBR = E/10;

E = Resilient modulus of subgrade (MPa).

In field, by knowing the geometric characteristics of existing pavement structure and obtaining the data of survey deflection measurements with FWD, it is possible, through the use of computer programs of backcalculation, estimate the resilient moduli of materials and, consequently to determine the correspondent structural coefficients to calculate the SNC.

2.2 Deflection Basin Parameters

All the deflection basin parameters used in this study are summarized in Table 1, that also shows a simple definition of each parameter.

Table 1 Deflection Basin Parameters.

Formulas	Unit	Definition	Reference
$A = 15 \cdot \left[1 + 2 \cdot \frac{D_{30}}{D_0} + 2 \cdot \frac{D_{60}}{D_0} + \frac{D_{90}}{D_0}\right]$	m	**Area Parameter** is a parameter combining all measured deflections in the basin.	[1]
$R = \frac{6250}{2(D_0 - D_{25})}$	m	**Radius of Curvature** is a parameter associated to the bending of the deformed basin.	[2, 3]
$SCI = D_0 - D_{30}$	10^{-2} mm	**Surface Curvature Index** is defined to better represent of the condition of upper layers.	[7]
$BDI = D_{30} - D_{60}$	10^{-2} mm	**Base Damage Index** is defined to be a good indicator for the base layer condition.	[7]
$BCI = D_{60} - D_{90}$	10^{-2} mm	**Base Curvature Index** is defined to be a good indicator of the condition of subgrade in aggregate base pavement.	[7]
D_{120}	10^{-2} mm	**D_{120}**, deflection at the distance of 120 cm from the plate center	-

Where D_0, D_{25}, D_{30}, D_{60}, D_{90} and D_{120} = deflections at the distances of 0, 25, 30, 60, 90 and 120 cm respectively, from the plate center (10^{-2} mm).

The paper defines correlations between pavements structural number and deflection basin parameters through two different approaches. The first one is theoretical correlation, based on computer simulations and the other one is called field correlation, based on field measurements and investigations.

3. Theoretical Correlation

For the theoretical study, it was simulated some flexible structures in software ELSYM-5. This computer program uses the layered linear elastic theory in order to calculate displacements, as well as stresses and strains at given depths in the pavement.

In these simulations, it was considered an application of a single wheel load of 40 KN applied through a 15cm radius base plate to resemble the loading of the pavement as for a FWD test.

Table 2 illustrates the values of resilient moduli, Poisson´s ratio and layer thicknesses, used for 324 theoretical simulations of three layered linear elastic system.

Due to the theoretical studies developed, it is possible to find out several mathematical models relating the modified structural number (SNC) to deflection basin parameters (A, R, SCI, BDI, BCI, D_0 and D_{120}), obtained through formulas from Table 1 and data from ELSYM-5 software, according to the parameters presented in Table 2.

The statistical regression approach was adopted to find the correlations between SNC and deflection basin parameters.

It is presented in Table 3 the expressions found through the simulations developed exclusively for the flexible pavement, composed by subgrade, granular base and asphaltic surface course.

4. Field Correlation

Aiming at mathematical correlations development between deflection basin parameters from non-destructive testing (NDT) using the FWD and the pavement's SNC in field. The data obtained from a survey on three road segments in Brazil were studied.

The modified structural number values were calculated based on the characterization of the existing pavements layers on each road segment analysed. Destructive testing was conducted for layers thickness and material determination. Additional laboratory tests were performed for subgrade's CBR determination.

Table 2 Selected structures parameters for the theoretical study.

Layer	Moduli (kgf/cm²)	Poisson's Ratio	Thickness (cm)
Surface	7.500 / 15.000 / 30.000	0,35	5 / 10 / 15 / 20
Base	2.000 / 3.000 / 5.000	0,40	15 / 20 / 25
Subgrade	500 / 1.000 / 2.000	0,45	-

Table 3 Theoretical Correlation between SNC_T = f(DBP)

Equation	R^2	Equation	R^2
$SNC = 4,1069 \cdot D_0^{-0,3368} \cdot R^{0,2537}$	0,938	$SNC = 16,4942 \cdot SCI^{-0,4665}$	0,844
		$SNC = 41,3833 \cdot D_0^{-0,5885}$	0,825
$SNC = 32,3190 \cdot D_0^{-0,3174} \cdot SCI^{-0,2727}$	0,938	$SNC = 0,3940 \cdot R^{0,4481}$	0,822
$SNC = 2,8305 \cdot \left(\dfrac{R}{D_0}\right)^{0,2889}$	0,935	$SNC = 15,9350 \cdot BDI^{-0,5647}$	0,791
$SNC = 8,0030 \cdot D_0^{-0,5929} \cdot A^{0,4326}$	0,920	$SNC = 7,1231 \cdot BCI^{-0,3310}$	0,379
$SNC = 0,0243 \cdot D_{120}^{-0,5653} \cdot A^{1,6542}$	0,886	$SNC = 0,8329 \cdot A^{0,4063}$	0,090

Table 4 Field characterisation of road segments.

Road Name	Surface		Base		Subbase	
	Material	Thickness (cm)	Material	Thickness (cm)	Material	Thickness (cm)
SP-255	AC	13,0	GRANULAR	10,0	SOIL	17,0
SP-253	AC	4,0	GRANULAR	16,0	SOIL	20,0
SP-261	AC	3,5	GRANULAR	17,0	SOIL	-

The resilient moduli of each pavement layers were determined from backcalculation, using deflection basin measurements and the thicknesses obtained from destructive testing. Table 4 presents the layer thicknesses and materials of the pavement sections in study.

Layer moduli backcalculation was performed using the ELMOD software, a specific program for the mechanical calculation and structural evaluation, developed by Dynatest Inc. Using the data from survey deflection measurements, the program calculates the resilient moduli through two backcalculation processes. The first considers just the radius adjustment of the basin deformation. The second method, more complex, calculates the moduli through the adjustment of field and theoretical deflection basins.

To achieve the maximum efficiency of the program, it is necessary to carry out the calculation through these two different processes. The first is essential for the calibration of constituent relations, and the second, to really calculate the resilient moduli.

The average backcalculated resilient moduli values of each layer of the pavements sections are presented in Table 5. It is important to highlight that the correlations between SNC and measured deflection basin parameters were conducted using the backcalculated moduli for all the FWD testing points. Therefore, the average values are presented only for road sections pavement characterization.

The following Table 6 presents correlations found between the SNC and deflection basin parameters (DBP), with the data of experimental road segments, consisting by flexible pavements with granular base.

Table 5 Backcalculated resilient moduli.

Road Name	Surface	Base	Subbase	Subgrade
	E_1 (kgf/cm²)	E_2 (kgf/cm²)	E_3 (kgf/cm²)	E_4 (kgf/cm²)
SP-255	51.883	2.402	-	3.080
SP-253	32.314	7.363	5.919	2.920
SP-261	48.460	1.377	-	753

Table 6 Field correlation between SNC_F = f(DBP).

Equation	R^2	Equation	R^2
$SNC = 84{,}0948 \cdot D_0^{-0{,}6068} \cdot A^{-0{,}2124}$	0,904	$SNC = 0{,}3010 \cdot R^{0{,}4864}$	0,798
$SNC = 87{,}4158 \cdot D_0^{-0{,}6948} \cdot R^{-0{,}0922}$	0,904	$SNC = 13{,}3757 \cdot BDI^{-0{,}4883}$	0,716
$SNC = 40{,}9143 \cdot D_0^{-0{,}6968} \cdot SCI^{0{,}0932}$	0,903	$SNC = 0{,}0299 \cdot D_{120}^{-0{,}7039} \cdot A^{1{,}6440}$	0,677
$SNC = 36{,}7105 \cdot D_0^{-0{,}5936}$	0,901	$SNC = 4{,}8044 \cdot BCI^{-0{,}2330}$	0,520
$SNC = 2{,}5954 \cdot \left(\frac{R}{D_0}\right)^{0{,}2735}$	0,864	$SNC = 10{,}6013 \cdot D_{120}^{-0{,}6116}$	0,474
$SNC = 17{,}0934 \cdot SCI^{-0{,}4896}$	0,812	$SNC = 0{,}0947 \cdot A^{1{,}0106}$	0,081

Table 7 Correlation between SNC x DBP [10, 11].

Base Type	Equation	R^2
Granular	$SNC = 10,73 \cdot D_0^{-0,5819} \cdot A^{0,3154}$	0,93
Granular	$SNC = 1,81 \cdot \ell n(R) - 5,34$	0,84

According to Refs. [10-12], the correlation between SNC, maximum deflection (D_0) and area parameter (A) has showed a good R^2 value, just like the correlation with SNC and the radius of curvature (R), those correlations are presented in the following Table 7.

For illustration, are presented the models of correlation proposed by the HDM-4 software between SNC and the maximum deflection [6] for the granular base pavements and cement treated base. It is noteworthy that HDM-4 correlations were developed based on deflections measured with the Benkelman beam equipment.

$$SNC = 57,29 \text{ x } D_0^{-0,625} \text{ – granular base} \quad (3)$$

$$SNC = 38,91 \text{ x } D_0^{-0,623} \text{ – cement treated base} \quad (4)$$

The original equations are presented in terms of inches; therefore, (3) and (4) represents the mathematical adjustment for the units usually used in Brazil, namely, D_0 in 10^{-2} mm.

5. Models Analysis and Selection

Based on available literature, it is noted that there is a good correlation between the pavement maximum deflection and its modified structural number (SNC). A good example is given by the HDM-4 software, which uses the expressions (3) and (4) to calculate the SNC, based on deflection measurements obtained in field testing from the Benkelman Beam device.

However, it is notoriously known the fact that pavements with the same maximum deflection may have different structural behavior, this fact is clearly demonstrated by comparing pavement deflection basins. The characterization of deformation basins is impracticable with Benkelman Beam device, but it is easily and quickly measured with FWD equipment, which is already widely used in Brazil.

Looking for more precise correlations to better represent the pavements structural characteristics, the modified structural number (SNC) was correlated to others basin deflection parameters besides maximum deflection. Thus, computer simulations were performed with the ELSYM-5 software and field testing was conducted using the FWD equipment on highway in the State of São Paulo, Brazil.

Both data, from computer simulations and field testing, were used to achieve good correlations between SNC and basin deflection parameters. The Table 4 shows the resulted correlations from computer simulations and Table 8 presents the correlations found with the field testing data. According to the Tables 4 and 8, it is noted from correlations with two variables that R^2 value is greater than in models with one single variable, especially when it was inserted the area parameter (A) and the radius of curvature (R) in the correlations. This happened for both, theoretical and field data.

The area parameter (A) is a measure that intends to characterize the shape of the deflection basin, since it uses for its calculus deflections up to 90 cm from the plate center. Hence, in this paper, this parameter is highlighted on the found correlations.

In Brazil, to characterize the basin, is frequently used the radius of curvature (R), and for its calculus are used both maximum deflection (D_0) and the one measured 25 cm from the plate center. In FWD testing, where usually are taken deflection at 20 cm and 30 cm from the plate center, the D_{25} value must be estimated, frequently with linear relations.

Combined with the maximum deflection (D_0), both parameter (area parameter and radius of curvature) improved the correlations, presenting R^2 values closest to 1. Therefore, were taken from computer and field data the correlation that uses D_0 and A and the ones that uses D_0 and R, and they were compared.

Maximum deflection (D_0), area parameter (A) and radius of curvature (R) values were simulated using the ranges of 20×10^{-2} mm to 250×10^{-2} mm, 20 cm to 60 cm and 40 m to 800 m, respectively. Then, the calculated SNC values, for both, theoretical and field correlations,

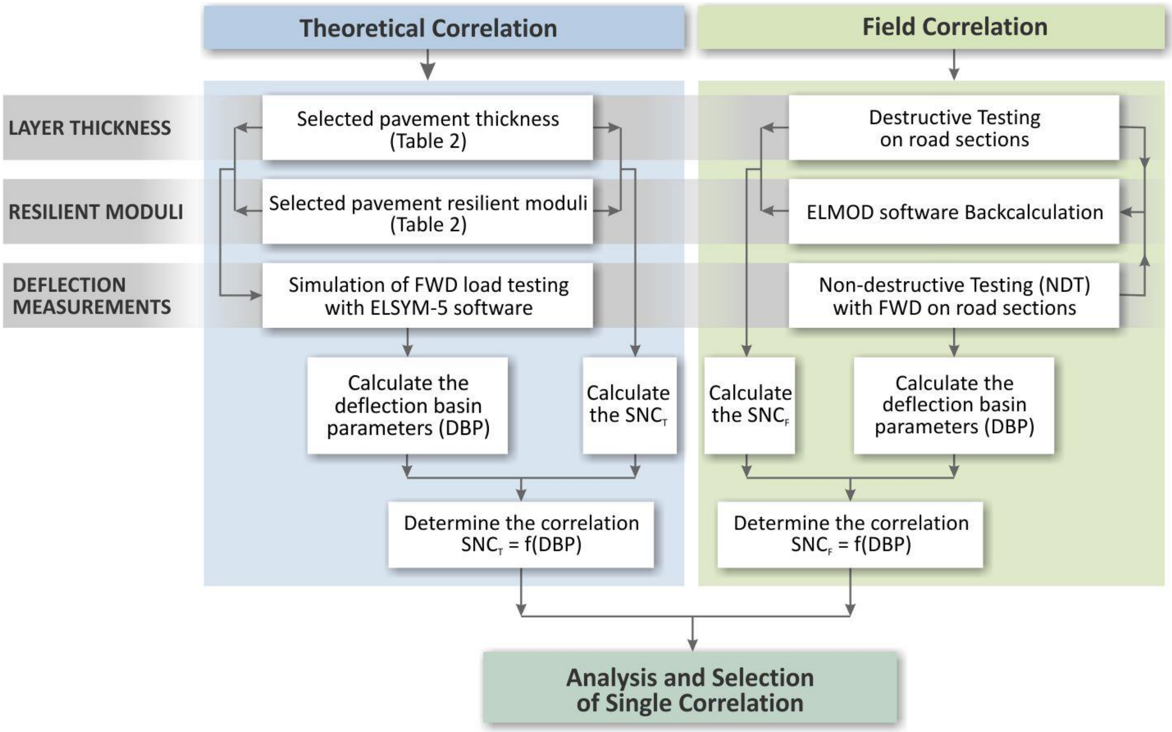

Fig. 1 Flowchart of the methodology.

were compared. A ratio between theoretical and field values close to 1 was observed for both correlations, using D_0, A and D_0, R. That shows a good fit between the theoretical correlation and the field data.

The correlations recommended for assisting a simplified structural evaluation and which will estimate the modified structural number of the existing flexible pavement are given below:

$$SNC_T = 4{,}1069 \times D_0^{-0{,}3368} \times R^{0{,}2537} \quad (5)$$

$$SNC_T = 8{,}0030 \times D_0^{-0{,}5929} \times A^{0{,}4326} \quad (6)$$

A simplified flowchart is shown in Figure 1. The flowchart illustrates the methodology used in this study, aiming to determinate an acceptable correlation between structural condition and deflection parameters.

6. Conclusion and Recommendations

The structural number of a pavement represents its capacity of supporting the traffic loading. Knowing this parameter in the rehabilitation projects is very useful. Usually, rehabilitation projects are based on deflection testing where only the maximum deflection is used to set the solutions.

Determining the area parameter (A) and the maximum deflection (D_0) soon afterward the construction enables the inspection to estimate SNC values in field and easily compare with the designed values. Additionally, knowing the thicknesses of each layer, the values of the resilient moduli can also be estimated and used on the technology control of the homogeneity of the execution.

According to that, it is clear the importance and advantage by using of several deflection data of the deformation basin, instead just the maximum deflection value.

The mathematic models presented in this paper enables, with the deflection parameters of the deformation basin and the future traffic data, to define strategies of rehabilitation for existing pavements.

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