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STRUCTURAL ANALYSIS OF FLEXIBLE ROAD PAVEMENTS

The focus of most road agencies around the world, and even in developing countries, is shifting nowadays from construction of new road sections to maintenance, rehabilitation and improvement of the existing road networks. Having accurate information about the condition and remaining service life of pavements is fundamental for their efficient maintenance. The objective of this paper is to present review of different approaches available for analysis of pavement structural condition, both at network and project levels. Paper presents review of the most widely used deflection measuring devices with focus of newly developed devices for continuous network level measurements at highway speeds and provides review of available tools and techniques for assessment of pavement structural capacity.

Keywords: pavement structural capacity, deflection, deflection basin parameters, Backcalculation

1. INTRODUCTION

The focus of most road agencies around the world, and even in developing countries, is shifting nowadays from construction of new road sections to maintenance, rehabilitation and improvement of the existing road networks which deteriorate due to the combined influences of traffic and environmental loads.

Having accurate information about the condition and remaining service life of pavements is fundamental for their efficient maintenance. Pavement evaluations are conducted to determine functional and structural conditions of a road sections either for purposes of routine monitoring or planned corrective action. Functional condition is primarily concerned with the ride quality or safety aspects of a road section (longitudinal and transverse evenness, surface texture and skid resistance, cross slope, splash and spray, etc.). Structural condition is concerned with the structural capacity of the pavement as measured by deflection, layer thickness, and material properties. In addition, visual condition surveys are used to assess both pavement functional and structural condition, but generally serve as a qualitative indicator of overall condition.

The pavement surface condition can be readily observed. However, subsurface information concerning the base and subbase courses and subgrade is costly to gather and interpret with destructive testing (i.e. coring, boring, trenching); this is why non-destructive (NDT) methods, particularly deflection testing are commonly used for pavement structural evaluation. Use of NDT also minimizes disruption to traffic, which is essential for heavily trafficked roads and airports. NDT can also be used as a screening tool to determine locations where selective material sampling should be conducted to evaluate other material properties in the laboratory. As such, its focus is to assess in situ properties that can be used to evaluate the need for further "destructive" testing, location of that destructive testing, and the current structural capacity of the highway as related to layer stiffness and strength.

The objective of this paper is to present review of different approaches available for analysis of pavement structural condition, both at network and project levels.

2. ANALYSIS METHODS

Although deflection measurements are relatively standard for pavement monitoring, improving the quality of the measurements and the interpretation of the test results is still an important issue.

The deflection analysis methods may be categorized in one of the following categories:

- Maximum deflection and deflection basin parameters (shape factors),
- Surface, composite, or pavement modulus approaches, including AASHTO '93 procedure [1], and
- Backcalculation of pavement layer moduli.

2.1 MAXIMUM DEFLECTION AND DEFLECTION BOWL (BASIN) PARAMETERS

The maximum (central) pavement deflection represents the overall bearing capacity of the pavement structure and subgrade and it is still used as the most important parameter for pavement rehabilitation design and for delineation of homogeneous sections (Figure 1). The limits between homogeneous sections are defined as locations where chart of cumulative differences changes slope.

Figure 2 presents an example of pavement rehabilitation criteria based on maximum deflection.

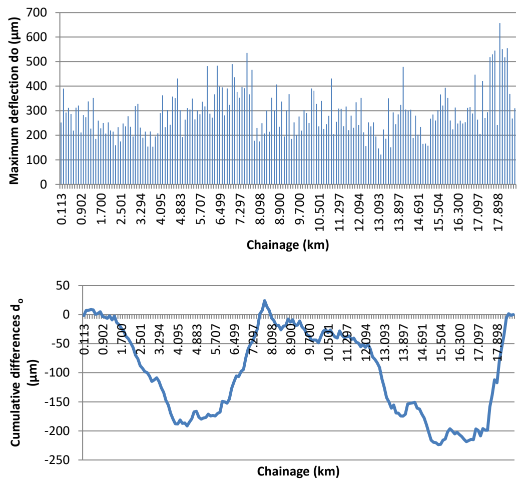

Figure 1. Chart of maximum deflections and homogeneous sections based on cumulative differences approach

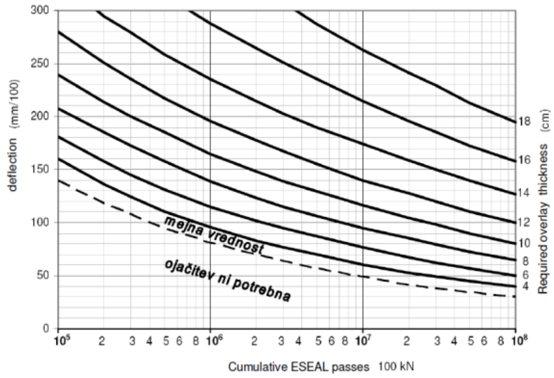

Figure 2. Overlay thickness criteria based on maximum deflection [5]

However, deflection basins, typically obtained by FWD, provide more useful information for better understanding of pavement condition and structural capacity. If maximum deflections are same, the higher curvature of the deflection basin in the vicinity of load indicates the weaker bound layers on the top of the pavement. Similarly, lower outer deflections are obtained on pavements on stiffer subgrades.

Horak [2] has defined three zones that characterize deflection bowl measured under a loaded wheel (Figure 3). In Zone 1, which extends to up to 300 mm from the loading, the deflection basin has a positive curvature. Zone 2 is called inflection zone where the deflection bowl switches from positive to negative curvature. This zone typically lies between 300 mm and 600 mm from the loading, but exact limits depend on pavement type and structure. Zone 3 includes the furthest part of the deflection basin from the loading, till approximately 2000 mm, which depends on the pavement structure and subgrade. The deflections within these three zones are related to various depths (layers) within the pavement structure.

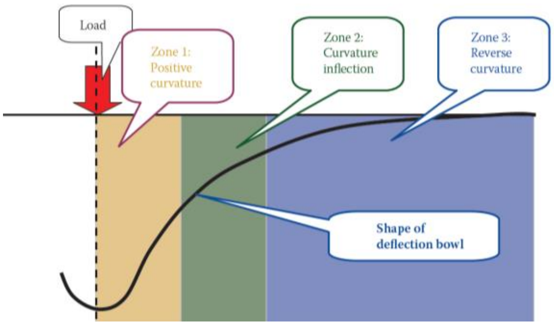

Figure 3. Summary of deflection bowl parameters [2]

Several deflection bowl parameters may be used to characterize pavement surface deformation under the loading. Table 1 presents some of most frequently used parameters.

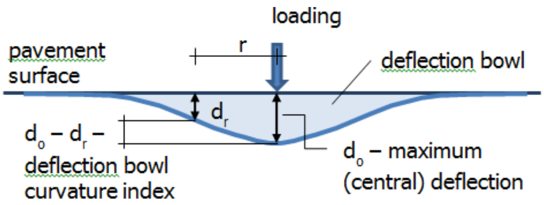

Figure 4. Deflection bowl parameters

Table 1. Deflection bowl parameters

Parameter	Designation/ Expression	Unit	Indication
Maximum deflection	d_0	μm	The overall pavement condition
Other deflections	d_r	μm	Layer condition at equivalent depth r
Radius of Curvature, RoC	$RoC = \frac{200^2}{2 \cdot d_o \cdot \left(1 - \frac{d_{200}}{d_0}\right)}$	μm	Fatigue of asphalt layers
Surface Curvature Index, SCI	$d_0 - d_{300}$ $(d_0 - d_{200})$	μm	Fatigue of asphalt layers
Base Damage Index, BDI	$d_{300} - d_{600}$	μm	Base condition
Base Curvature Index, BCI	$d_{600} - d_{900}$	μm	Subbase condition
Deflection basin Curvature Factor, CBF	$(d_0 - d_r) / d_0$	-	Layer condition at equivalent depth r
Deflection Ratio, DR	d_0 / d_r	-	Layer condition at equivalent depth r

In addition to definitions presented in Table 1 that are mostly used in the literature, there are additional definitions of these parameters, sometimes under different names, or using different deflections. For example, Talvik and Aavik [9] define BCI as difference between deflections at 1200 and 1500 mm from the point of loading, and use this indicator to assess the subgrade condition. Therefore, it is critical to understand the physical meaning of each parameter and to consider it in the context of particular pavement structure, because they may have different importance for thick or for thin pavements.

For Do, RoC, SCI, BSI and BCI, Horak and Emery [3] determined benchmark classification for various flexible pavement sections.

In addition, AREA parameters that present the surface of deflection basin are widely used in the pavement structural capacity analysis. $AREA_{36}$ is widely used for analysis of rigid pavements, while $AREA_{12}$ is used for flexible pavements.

$$AREA_{36} = 6 \cdot \left(1 + 2 \cdot \frac{d_{300}}{d_0} + 2 \cdot \frac{d_{600}}{d_0} + \frac{d_{900}}{d_0}\right) \quad (1)$$

$$AREA_{12} = 2 \cdot \left(2 + 3 \cdot \frac{d_{200}}{d_0} + \frac{d_{300}}{d_0}\right) \quad (2)$$

Deflection basin parameters provide simple and sound way to assess the pavement structural capacity that is not dependent on the knowledge of pavement structure, which is often not available. They can easily be used for network level assessment, but also represent a valuable tool that can be used for project level assessment.

2.2 SURFACE, COMPOSITE, OR PAVEMENT MODULUS APPROACHES

The surface modulus is the "weighted mean modulus" of an equivalent half space of a material with uniform modulus. It is calculated using Boussinesq's equations:

$$E_o(0) = 2 \cdot \left(1 - \mu^2\right) \cdot \sigma_o \cdot \frac{a}{d(0)} \quad (3)$$

$$E_o(r) = \left(1 - \mu^2\right) \cdot \sigma_o \cdot \frac{a^2}{r \cdot d(r)} \quad (4)$$

where:
$E_o(r)$ -surface modulus at a distance r from the center of the loading plate
μ - Poisson's ratio (usually set equal to 0.35)
σ_o - contact stress under the loading plate
a - radius of the loading plate, and
d_r - deflection at the distance r.

The surface modulus plot (E_o versus r) provides:

i. An estimate for subgrade modulus (or CBR)

ii. Immediate determination of whether the subgrade modulus is linear elastic or non-linear, giving an indication of likely soil type, and
iii. Confirmation of the adequacy of the geophone settings (as shown in Figure 5)

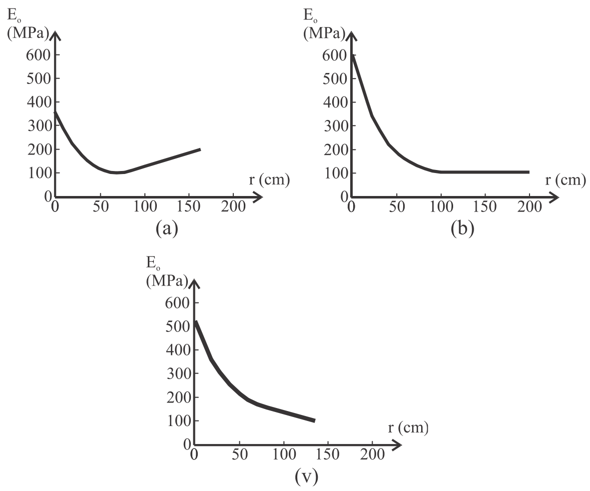

Figure 5. Surface modulus plot (a) with non-linear elastic subgrade modulus, (b) with linear subgrade modulus and (c) where geophones are too close

At relatively large distances (generally more than 600 mm) from the loading plate, all compressive strain will occur in the subgrade rather than in the pavement layers which lie outside the stress bulb. For this reason the outer deflections will be uninfluenced by the pavement structure, i.e. the surface modulus will tend to the modulus of the subgrade alone.

When outer deflections show an apparently increasing modulus (case a), this is indication of non-linear subgrade. Case (b) presents the linear subgrade performance, where subgrade modulus does not depend on the distance to loading. Finally, case (c) is related to thick, stiff pavement, where geophones are located too close to loading plate and there may be softer soils beyond the range of geophone assembly. In this case the geophone spacing should be increased so that at least the three outer geophones define a linear segment on the surface modulus plot.

AASHTO/93 Guide [1] includes three approaches for determination of existing pavement structural capacity. The first two approaches, that are less used, include analysis of distresses and past traffic loading. The mostly used approach is based on deflection measurements, and analysis of two layered structure, composed of pavement considered as a composite layer, and subgrade, as presented in Figure 6.

The subgrade resilient modulus M_R is first determined based on one of outer deflections, which should be ideally located at distance r larger than the radius of stressed zone on the surface of subgrade a_e. The subgrade resilient modulus is equal to the surface modulus calculated from outer deflections and the approach typically includes determination of surface modulus minimum value, and check if that value is determined from deflection sensor located outside of the stressed zone in pavement.

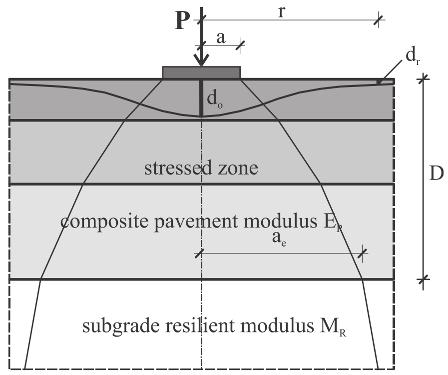

Figure 6. Parameters of pavement structure and deflection basin used in the AASHTO/93 approach

When the subgrade resilient moduli is known, the composite pavement modulus E_p and pavement effective structural number SN_{xeff} can be calculated from maximum deflection d_o using equations (5) and (6).

The AASHTO approach provides relatively simple way for determination of pavement structural capacity and overlay design, since it is consistent with AASHTO procedure for design of new pavements. In addition, the overlay thickness can be easily calculated for all deflection points if pavement total thickness is reasonably available and homogeneous sections may be defined based on overlay thickness, using the method of cumulative differences. On that way, the approach would account for spatial variability of data.

$$SN_{xeff} = 0.0237 \cdot D \cdot \sqrt[3]{E_P} \quad (5)$$

$$d_o = 1.5 \cdot \sigma_o \cdot a \cdot \left[\frac{1}{M_R \sqrt{1+\left(\frac{D}{a}\cdot\sqrt[3]{\frac{E_P}{M_R}}\right)^2}} + \frac{1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}}{E_P} \right] \quad (6)$$

where:

d_o – maximum deflection (mm), corrected to 20°C

σ_o – contact stress (kPa)

P – deflectometer loading (kN)

D – pavement total thickness (m)
a – radius of contact plate (0.15 m for Dynatest FWD, 0.225 m for KUAB FWD)
M_R – subgrade resilient modulus (MPa)
E_p – pavement composite modulus (MPa).

2.3 PAVEMENT AND SUBGRADE MODULI BACKCALCULATION

The mechanistic empirical approach, that is based on calculation of moduli, stresses and strains in pavement layers and relating them to past experience of pavement performance, is being used more and more instead of empirical methods based on bowl parameters for evaluation of pavement structural capacity.

A major advantage of analytical or mechanistic structural design methods over more empirical methods is that the former may be used with any type of material and structure, and under all climatic conditions (provided that fatigue criteria are established for each material type). The latter, on the other hand, may be applicable only under the conditions for which the empirical relationships were developed.

Pavement layers and subgrade modulus backcalculation is the most sophisticated approach to assess pavement structural capacity based on deflection testing. This is an iterative procedure in which the initially presumed layer moduli are adjusted until the best match is achieved between the predicted and measured surface deflection values. A straightforward linear elastic approach is generally favored in routine FWD analysis [9], although this procedure can also take into account non-linearity of materials in subgrade and subbase, history of loading and pavement surface deflection, material anisotropy etc.

The approach may include manual iterations, when the backcalculation is begun by making a surface modulus plot, then calculating the subgrade modulus, then the unbound base modulus and finally the modulus of asphalt layers. These values can then be manually adjusted based on engineering judgement, in an iterative manner until predicted and measured deflections match acceptably. The iterative process can be automated, and in that case may start from a set of layer moduli which may or may not be user defined (seed moduli). Finally, there are approaches that are based on soft computing methods (artificial neural networks and genetic algorithms) and use databases with large number of deflection bowls. In addition to static backcalculation, there is option to use time history of loading and deflections and perform dynamic backcalculation since FWD test in inherently dynamic. This approach takes advantage of more information provided by the test, which allows for backcalculating more parameters such as layer thicknesses or the modulus versus frequency curve of the HMA layer.

For static backcalculation approach, knowing accurate pavement layer thicknesses is of critical importance, since minor variations of layer thickness during construction, if not accounted for, can result in major errors in backcalculated layer moduli [4]. Because most of the measured deflections is dominated by the nature of the subgrade, it is important that its stiffness is accurately modelled. Otherwise backanalysis would result in disproportionately large errors of upper layers moduli [6]. Procedure is not sensitive to the values of Poisson's ratio, and values between 0.35 and 0.45 are typically used in the analysis. Generally, it is recommended that the model should contain only one asphalt layer (all asphalt layers are combined in one) and that moduli decrease significantly with depth (an Ei/Ei+1 ratio of greater than two is sometimes recommended).

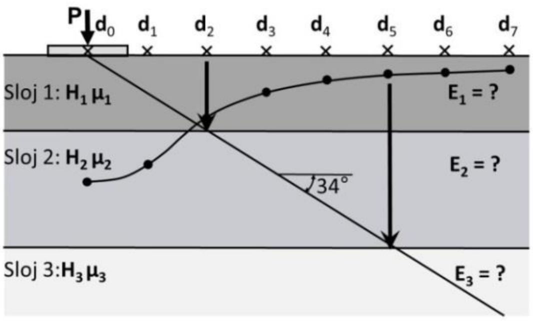

Figure 7. The principle of pavement layer moduli backcalculation

A large number of computer programs for doing automated backcalculation have been developed. Among the more widely used programs are the following:

- ELMOD (Dynatest)
- EVERCALC (Washington State DOT)
- MODCOMP (Cornell University)
- MODULUS (Texas A&M University)
- PADAL (University of Nottingham)
- WESDEF (U.S. Army, Waterways Experiment Station)

Most of the automated backcalculation programs rely on an elastic layer program, except ELMOD which is based on Odemark's Method of Equivalent Thicknesses [11]. The FHWA report [7] provides more extensive overview of the available backcalculation software.

Most of these programs involve the use of numerical integration subroutines that are capable of calculating FWD pavement deflections and other parameters, if stiffness (or moduli) and thicknesses of the various pavement layers are known. If all assumptions are correct, meaning each layer is an elastic layer, is isotropic and homogeneous, and all other boundary conditions are correct, then it is possible to iterate various combinations of moduli until there is a sufficiently close match between measured and theoretical FWD deflections.

A major drawback to this approach is the fact that one or more of the many input assumptions mentioned above may be incorrect and therefore do not apply to the actual in situ pavement system. Despite this, the procedure reaches very reasonable and rational moduli values in most cases. This conclusion appears to be especially true when relatively intact, well-defined, and un-distressed pavement sections are tested with FWD. However, it is critical that the engineer using a backcalculation program of choice should be very well versed in its proper use and inherent limitations. Accordingly, backcalculation is arguably more of an art than a science [9].

3. CONCLUSION

The paper summarized the available approaches for analysis of pavement structural capacity and provided review of deflection basin parameters and approaches based on calculation of surface, or subgrade and pavement composite moduli. These approaches provide simple way to assess the pavement structural capacity, especially in case when limited other information on pavement construction history, structure and past traffic are available.

If sufficient information is available, mechanistic approach that assumes backcalculation of subgrade and pavement layer moduli is the most advanced and recommended for evaluation of pavement structural capacity and several computer programs are available for pavement moduli backcalculation.

Several important issues, like spatial and seasonal variations, including variations of layer thicknesses, temperature and moisture conditions, material non-linearity, and depth to stiff layer have also been addressed in the paper. They illustrate how important it is to be aware on all limitation of theory and to have deep understanding of material and layer properties and stress and strain conditions within the pavement and the subgrade in order to achieve reasonable assessment of layer moduli.

“The backcalculation is more art than science” used to say two gurus of backcalculation, prof. Lynne Irwin and Richard Stubstad. This should always be kept in mind!

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