CETRA2024 15-17 May 2024, Cavtat, Croatia
8th International Conferenceon Road and Rail Infrastructure

FALLING-WEIGHT-DEFLECTOMETER-BASED STRUCTURAL CONDITION ASSESSMENT OF LOW-VOLUME ROAD PAVEMENTS: PRACTICES AND CHALLENGES

Martynas Karbočius, Audrius Vaitkus
Vilnius Gediminas Technical University, Road Research Institute, Lithuania

Abstract

Falling weight deflectometer (FWD) is widely used as one of the most reliable and cost-effective methods to assess the bearing capacity of a pavement structure and its separate layers. Although FWD-based bearing capacity measurement and evaluation techniques were fairly well developed over several decades, little attention was paid to roads with low traffic flow. The applicability of existing techniques to evaluate bearing capacity of low-volume road pavements is limited. Furthermore, the results of the analysis may be inconsistent with the complete set of data, which includes visual pavement condition and structure material sampling data. This leads to subjective treatment of research results and the risk of questionable decisions. This article reviews commonly used pavement bearing capacity analysis techniques and presents the practice applied in Lithuania. Case studies on low-volume roads highlight limitations and possible improvements in methodology to optimise the assessment of the pavement condition of low-traffic roads and related decision-making.

Keywords: falling weight deflectometer, deflection basin, structural condition, low volume roads, flexible pavement

1 Introduction

Low-volume regional and local roads cover a significant part of the road network. The application of maintenance, repair, and rehabilitation based on a reliable assessment of the condition of the pavement structure leads to economically efficient road management and ensures the condition of the infrastructure that meets public expectations. Widely applied methods of assessing the condition of existing pavements, such as visual assessment of pavement surface deterioration and coring, are time and money consuming and do not allow direct assessment of the essential aspect, the behaviour of the pavement structure under traffic loads. For this purpose, the falling weight deflectometer (FWD) has been used for several decades. Bearing capacity measurement and evaluation techniques based on FWD are fairly well developed. They include direct FWD measurement data, i.e. analysis of the deflection basin and its parameters, such as peak deflection, different deflection basin parameters, back-calculation of the layer moduli for mechanistic analysis. However, practice shows that existing techniques are more reliable for evaluating heavy-duty road pavement structures. The applicability to the evaluation of low-volume road pavements is limited, and the results of the analysis, especially the backcalculation, may be inconsistent with the full set of data, which includes visual pavement condition and destructive test data. This leads to subjective treatment of research results, based on experience, interpretations, and assumptions, which create uncertainties and the risk of questionable decisions.

DOI: https://doi.org/10.5592/CO/CETRA.2024.1613

2 Review of existing techniques for assessing pavement structural condition

The most widely applied, especially at the project level, is the indirect use of FWD measurement data to calculate the residual life of an existing structure and for rehabilitation design using a mechanistic-empirical approach. The process is based on an iterative calculation of the moduli of each layer of the pavement structure and the subgrade from the deflection measured by FWD. Despite the effectiveness of the method, it requires a deeper analysis and knowledge-based judgment.

The results of backcalculation can be highly variable due to variability in pavement condition, subsurface condition, material properties, layer thickness along the road, and even the software used [1]. Researchers also indicated non-linear behaviour of the subgrade and the presence of a stiff interlayer as challenging aspects for backcalculation analysis [2-6]. Backcalculation analysis is particularly complicated for low-traffic road pavements. In addition to the factors mentioned above, thin asphalt and unbound base layers, the use of soft asphalt, cement-treated base layer, and other unconventional materials can be mentioned [7, 8]. Since the asphalt layer on low-volume roads is usually thin and is directly in the loading zone, unreasonable values of the modulus of the asphalt layer are usually obtained. Relatively reliable backcalculation analysis is generally considered limited to the thickness of the asphalt layer of at least half the radius of the load plate [1]. Furthermore, researchers identify challenging backcalculation analysis of structures with cement-treated base layers or stabilised subgrade [9-11] due to the unusual stiffness profile of the structure. Cement treatment is becoming a particularly popular technology on low-traffic roads as a complete or partial replacement of unbound layers due to lower costs and relatively high bearing capacity.

One of the potentially best support tools for assessing structural condition is deflection basin data analysis. Various deflection basin paremeters were derived for the preliminary assessment of the condition of the pavement layers, the identification of homogeneous sections, anomalies, and target locations for a more detailed analysis. Table 1 summarises some commonly used parameters of the deflection basin that have been reported to correlate with the structural condition of the pavement and the stress and strain used for the mechanistic analysis [12-15]. However, many regression analysis models are based on data generated by multilayer linear elastic or finite element analysis and, therefore, are not widely used. Especially considering the most important purpose of the deflection basin parameters as a primary pavement condition analysis and decision support tool, rather than a way to replace or oversimplify the mechanistic pavement design.

Table 1 Deflection basin parameters

Structural condition index	Equation	Indication of structural conditions
d_0	–	Overall
Base Layer Index *BLI*	$d_0 - d_{300}$	Upper layer
Middle Layer Index *MLI*	$d_{300} - d_{600}$	Base layer(s)
Lower Layer Index *LLI*	$d_{600} - d_{900}$	Subgrade
AREA	$\frac{6\left(d_0 + 2d_{300} + 2d_{600} + d_{900}\right)}{d_0}$	Upper layer
Area Under Pavement Profile *AUPP*	$\frac{5d_0 + 2d_{300} + 2d_{600} + d_{900}}{d_0}$	Upper layer
Here, d_i is the normalised deflection at a distance i from the centre of the load plate.		

Some studies have focused on determining the reference values of the deflection basin parameters, helping to more easily assess the condition of the pavement. Horah et al. [16] proposed a three-level benchmarking for the parameters d_0, *BLI, MLI,* and *LLI,* based on the type of base layers, including granular, cementitious, and bituminous base. However, the applicability of such a scheme is limited by different road construction practices of the countries and the most important aspects that the value of the parameter is determined not only by the structural condition but also by the composition of the pavement. The same parameter value may be a typical indication of good condition for one structure, yet may indicate deterioration for another. Therefore, benchmarking cannot be generalised to all structures.

In Lithuania, the methodology adopted from German practice is currently used for the initial assessment of the condition of the pavement and the identification of possible structural problems. The methodology is based on the compliance of two parameters M_0 and T_z with the reference limit values [17]. M_0 is the modulus of the unbound half-space and describes the bearing capacity of the unbound layers and subgrdae. T_z is a dimensionless parameter that determines the relative stiffness of the asphalt layers.

To calculate the unbound half-space modulus M_0, the deflection basin outside the load plate is approximated from the measured normalised deflection. It is described by the theoretical regression equation applied to a standard 300 mm diameter load plate:

$$d_{i,ri} = A \cdot \left(a_0 \cdot e^{B \cdot a_1 \cdot r_i} + a_2 \right) \tag{1}$$

where:

$d_{i,ri}$ – normalised deflection outside the load plate at distance r_i from the centre of the load plate [mm];

r_i – distance from the load plate centre [mm];

a_0 = 0,392948; a_1 = - 0,398483; a_2 = 0,0137024;

A – regression parameter of the deflection basin [mm];

B – regression parameter of the deflection basin [mm^{-1}].

The unbound half-space modulus M_0 is calculated according to the regression parameters of the deflection basin and the applied load:

$$M_0 = F \cdot \frac{B}{A} \tag{2}$$

where:

F – applied load [kN];

A – regression parameter of the deflection basin [mm];

B – regression parameter of the deflection basin [mm^{-1}].

The bearing capacity index T_z of the asphalt pavement is calculated according to the formula:

$$T_z = \left(\frac{R_0 \cdot 1000}{d_0} \right)^{0,5} \tag{3}$$

where:

R_0 – the radius of the deflection basin [m];

d_0 – normalised deflection under the load plate [mm].

The radius of the deflection basin is calculated according to Eqn. (3):

$$R_0 = 24{,}494\left(d_0 - d_{210}\right)^{-0{,}899} \tag{3}$$

where:
d_0 – normalised deflection under the load plate [mm];
d_{210} – normalised deflection at the distance r = 210 mm from the centre of the load plate [mm].

After determining the road design load, the bearing capacity parameters M_0 and T_z at each test point are compared with the benchmark values associated with the design load as indicated in Table 2. The design load intervals reflect the classification scheme of the standard structures catalogue used in Lithuania.

Table 2 Benchmark values for flexible pavement structures used in Lithuania

Design ESAL [10^6]	**0,1**	**0,3**	**1**	**2**	**3**	**10**	**32**	**100**
T_z [–]	0,15	0,17	1,48	2,38	2,67	3,02	3,65	4,35
M_o [N/mm²]	125	125	150	150	150	150	150	150

By comparing the calculated bearing capacity parameters with the benchmark values, the conformity of the bearing capacity of the asphalt pavement and the unbound layers with the design load is determined. Four condition categories are distinguished: 1) if both T_z and M_0 are higher than the benchmark values, the bearing capacity of the entire pavement structure is sufficient; 2) if T_z is higher than the benchmark value and M_0 is lower, the asphalt pavement is relatively stiff, but sensitive to stress due to the low bearing capacity of the base layers and/or subgrade; 3) if T_z is lower than the benchmark value and M_0 is higher, the stiffness of the asphalt pavement is relatively low, but the bearing capacity of the base layers and subgrade is high.
The greater applicability of the method is determined by linking the bearing capacity parameters with the design load intervals, which allow identification of the inconsistencies of the existing structure with the expected impact of the loads. Although practice has proven that the methodology is consistent and reflects the condition of the pavement structures designed for load greater than $1{,}0 \cdot 10^6$ ESAL, it shows contradictory results on low-volume roads with a design load of up to $0{,}3 \cdot 10^6$ ESAL. Several case studies representing typical situations have been selected to demonstrate the challenges and potential for improvement of the methodology applied in Lithuania.

3 Case studies

3.1 Site description

Nine low-volume road sections with typical pavement structures were selected to demonstrate the performance of the structural condition assessment methodology used in Lithuania (Table 3). First, pavements with equally good condition but designed for different load varying from $0{,}05 \cdot 10^6$ ESAL to $0{,}3 \cdot 10^6$ ESAL and resulting in variable layer thicknesses were selected. Comparison of the deflection data of these pavements gives insight into the characteristic deflection parameters of the undeteriorated pavements. Second, pavements designed for load up to $0{,}05 \cdot 10^6$ ESAL were additionally selected, varying in visual condition. The different visual conditions of the pavement allow one to evaluate the evolution of the deflection parameters due to the effect of traffic loads.

The pavement condition is defined by three levels: "Good", "Moderate", and "Severe" (Figure 1). Good condition is considered if there is no distress indicating structural deterioration. A moderate condition is considered if some fatigue cracks are present only to a minor degree, i.e., appear as longitudinal or hairline cracks and have not yet formed an interconnected network. Severe condition is considered when the pavement is dominated by alligator cracking and structural deformation.

Figure 1 Typical good (left), moderate (middle) and severe (right) pavement condition of the studied low-volume roads

The trailer-mounted FWD "PRIMAX 2500" was used for measurements with deflection sensors located at 0, 200, 300, 450, 600, 750, 900, 1200, 1500, 1800 and 2100 mm from the 150 mm radius load plate. A load of 50 kN was applied. The FWD test was performed in both traffic lanes at a 25-50 m interval in the outer wheel path. During the test, the air, surface, and pavement temperature was also recorded.

Table 3 Selected low-volume road sections

Section No.	Design load [10^6 ESAL]	Layer thickness [mm]			Subgrade treatment	Pavement condition
		HMA	Base	Subbase		
1	≤ 0,05	49-62	100-234	65-182	-	Severe to moderate to good
2	≤ 0,05	49-56	119-198	140-245	-	Severe to moderate to good
3	≤ 0,05	62-85	150-246	347-400	-	Moderate to good
4	≤ 0,05	60	200	390	Stabilised	Good
5	≤ 0,05	60	250	350	Stabilised	Good
6	≤ 0,1	100	200	250	-	Good
7	≤ 0,1	100	200	350	-	Good
8	≤ 0,3	120	200	230	Stabilised	Good
9	≤ 0,3	120	200	330	Stabilised	Good

3.2 Structural gondition assessment

To better understand the typical load response of pavement structures, sections or their parts with equally good condition, but designed for different load and resulting in variable layer thicknesses, were selected. Figure 1 shows the bearing capacity parametersM_0 and T_z of selected section pavement structures, calculated according to Eqn. (1) - (4).
From Figure 1, it can be seen that the pavement structures have a significantly higher bearing capacity than the benchmark values set in Table 3. All index T_z, values representing bearing capacity of asphalt layers, are not lower than 0,42, which is 2,3 and 2,7 times higher than the benchmark values of 0,17 and 0,15 at design loads of $0{,}3 \cdot 10^6$ ESAL and $0{,}1 \cdot 10^6$ ESAL, respectively. Differences between structures with different thicknesses of asphalt pavement are also visible.

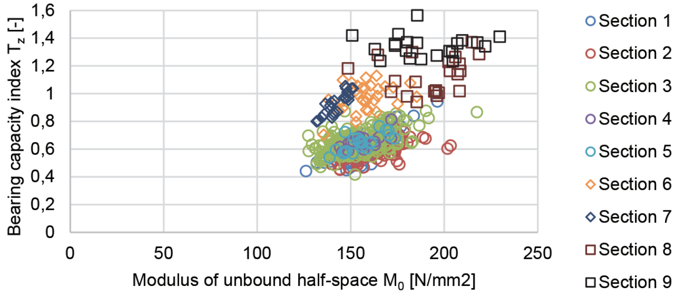

Figure 2 Deflection-based structural condition parameters of different pavement structures in good condition

In Sections 1-5, where the thickness of the asphalt pavement is 6-8 cm, the T_z values range from 0,42 to 0,87 with the highest concentration at approximately 0,55-0,80. The values in Sections 6-7 (10 cm asphalt pavement) are scattered between 0,80-1,13, and for Sections 8-9 (12 cm asphalt) pavement between 0,94 and 1,56, with the highest concentration at 1,13 to 1,37. It can also be seen that the modulus of the unbound half-space is mainly concentrated around 150 N/mm^2 and is closer to the benchmark values of structures designed to loads ≥ 1,0 $\cdot 10^6$. The M_0 below the value of 150 N/mm^2 is more characteristic of Sections 1-3, some subsections of which are already characterised by structural deformations, which may indicate a possible deterioration in subsections of good condition that has not yet occurred. This could be identified by further section observations. Another possible reason for this could be the fluctuating thickness of the layers, which can be observed from the data in Table 4, which is only compiled from destructive tests on a limited scale and should be verified by extended research.

To understand how the parameters M_0 and T_z change during pavement deterioration, sections with similar pavement structures (designed for 0,05 $\cdot 10^6$ ESAL) were selected. It was divided according to the condition into three general categories from "Good" to "Moderate" and "Severe". Figure 2 shows the bearing capacity parameters M_0 and T_z of selected pavement structures.

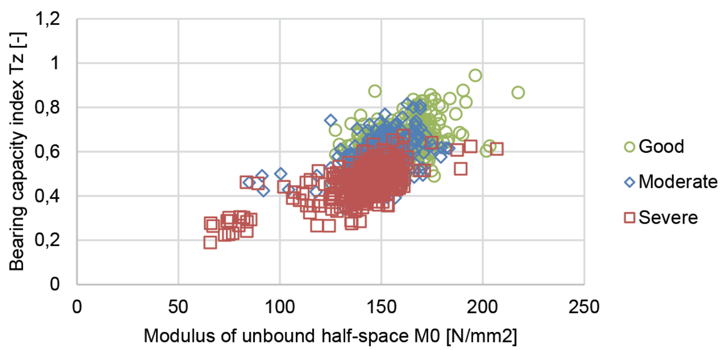

Figure 3 Distribution of deflection-based structural condition parameters according to visual condition

It can be seen that the parameters M_0 and T_z overlap to some extent but show a certain tendentious distribution according to the visual condition of the pavement, even when applying a rough general classification. T_z values in case of severe condition mainly concentrate up to 0,55. In the case of moderate visual condition, the T_z values are concentrated in the range of 0,47 to 0,63. In good condition, the T_z values are scattered between 0,54-0,94.

Even in the visually severe condition of the pavement, T_z does not reach the benchmark value used so far. A rather significant shift of the M_0 data below the value of 150 N/mm^2 in severe pavement conditions is also observed and the occurrence of extremely low values is characteristic. This shows that the parameters of the structural condition M_0 and T_z can potentially identify the insufficient bearing capacity of the low-volume pavement structure. However, more detailed studies are needed to explain the overlap and dispersion of the data.

4 Conclusions

A review of the most widely used pavement structural condition assessment techniques shows that there is an untapped potential to improve the pavement assessment process by incorporating deflection basin indices that can serve as a decision support tool alongside widely used methods such as backcalculation and mechanistic analysis. In particular, these indices would help in the assessment of low-volume road pavement structures bearing capacity and parameters of their separate layers, as the generally recognised backcalculation methodology is complicated.

The case analysis on low-volume roads shows that the methodology, based on the benchmarking of the asphalt layer bearing capacity index T_z and the modulus of the unbound half-space M_0 is potentially applicable to the assessment of the structural condition of low-volume road pavement structures. However, the revision of benchmark values is needed. Comparison of the parameters T_z and M_0 between the different classes of pavement structures in good condition generally shows a consistently different distribution, indicating the potential to review the benchmark values used so far, especially by increasing the benchmark value of the asphalt pavement bearing capacity index T_z, which seems to have been unreasonably low. The comparison of parameters T_z and M_0 between pavement structures of the same composition with different visual conditions showed that both parameters show a trending distribution through defined categories of visual conditions. However, even when the visual condition is severe and indicates structural problems of the pavement, the parameters, especially T_z, are higher than the benchmark values and indicate the need for improvement of the methodology.

As case studies only show the general potential to use the M_0–T_z methodology to assess structural condition in low-volume roads, extensive and more detailed research is necessary. It should include a larger number of representative roads constructed with different materials, a detailed determination of the actual thickness of the pavement structure layers by georadar, and destructive testing. This could explain the dispersion of data, the dependence of parameters on the use of different materials.

Acknowledgment

This research has received funding from the Research Council of Lithuania (LMTLT), the project “Civil Engineering Research Centre”, grant No. S-A-UEI-23-5.

References

[1] Pierce, L.M., Bruinsma, J.E., Smith, K.D., Wade, M.J., Chatti, K., Vandenbossche, J.: Using falling weight deflectometer data with mechanistic-empirical design and analysis, volume III: Guidelines for deflection testing, analysis, and interpretation, United States, Federal Highway Administration, 2017.

[2] Rwebangira, T., Hicks, R.G., Truebe, M.: Sensitivity analysis of selected backcalculation procedures, Transportation Research Record: Journal of the Transportation Research Board No, 1117 (1987), pp. 25-37

[3] Tutka, P., Nagórski, R., Złotowska, M., Rudnicki, M.: Sensitivity Analysis of Determining the Material Parameters of an Asphalt Pavement to Measurement Errors in Backcalculations, Materials, 14 (2021) 4, DOI: 10.3390/ma14040873

[4] Chai, G.W., Kelly, G., Chowdhury, S., Loo, Y.C., Manoharan, S.P., Golding, A.: Issues pertaining to Backcalculation of Stiffness Modulus in Flexible Pavements with Highly Nonlinear Subgrade Materials, 9th International Conference on Road and Airfield Pavement Technology, 2015.

[5] Salour, F., Erlingsson, S.: The influence of groundwater level on the structural behaviour of a pavement structure using FWD, International conferences on the bearing capacity of roads, railways and airfields, pp. 485-494, Trondheim, Norway, 25-27 June 2013.

[6] Lee, Y.C.: Condition Assessment of Flexible Pavements using FWD Deflections, Ph.D. Dissertation, North Carolina State University, Raleigh, NC, 1997.

[7] Vaitkus, A., Vorobjovas, V.: Alternative rehabilitation methods for low-volume roads, 3rd International Conference on Road and Rail Infrastructures - CETRA 2014 Split, Croatia, 28–30 April 2014.

[8] Gražulytė, J., Vaitkus, A., Vaidogas, E.R., Šernas, O.: Field studies of MSWI bottom ash as aggregate for unbound base course mixtures, IOP conference series: Materials science and engineering. Bristol: IOP Publishing, 1202 (2021), pp. 1-7

[9] Hossain, M.S., Nair, H., Ozyildirim, H.C.: Determination of mechanical properties for cement-treated aggregate base, Report No. FHWA/VTRC 17-R21, Virginia Transportation Research Council, 2017.

[10] Nakhaei, M., Timm, D.H.: A new methodology to improve backcalculation of flexible pavements with stabilized foundations, Construction and Building Materials, 368 (2023), 130405

[11] Timm, D., Tutu, K.: Determination of an Optimum Backcalculation Cross Section for Unconventional Pavement Profiles, Transportation Research Record, 2641 (2017) 1, pp. 48-57, DOI: 10.3141/2641-07

[12] Horak, E.: The use of deflection basin measurements in the mechanistic analysis of flexible pavements, Sixth international conference on the structural design of asphalt pavements, Michigan, USA, 13-17 July 1987.

[13] Kim, Y.R., Park, H.: Use of FWD Multi-Load Data for Pavement Strength Estimation, North Carolina Department of Transportation, 2002.

[14] FHWA, Pavement structural evaluation at the network level: final report, Federal Highway Administration, Publication no. FHWAHRT15/074, 2016.

[15] Saleh, M.: A mechanistic empirical approach for the evaluation of the structural capacity and remaining service life of flexible pavements at the network level, Canadian Journal of Civil Engineering, 43 (2016), pp. 749–758, DOI: 10.1139/cjce-2016-0060

[16] Horak, E.: Benchmarking the structural condition of flexible pavements with deflection bowl parameters, Journal of the South African Institution of Civil Engineering, 50 (2008) 2, pp. 2-9

[17] Forschungsgesellschaft für Straßen- und Verkehrswesen: Arbeitspapier Tragfähigkeit Verkehrsflächenbefestigungen, Teil C 2.1: Falling Weight Deflectometer (FWD): Auswertung und Bewertung – Asphaltbauweise, Köln, 2014, FGSV 433 C 2.1.