SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I8P124

Volume 13 Issue 8, 397-413, August 2026

Original Article

A Deflection Basin Parameters Based Approach to Enhance Seed Moduli Estimation in Three-Layer Flexible Pavements Backcalculation

Satyanandam Gangisetti[1], Sunny Deol Guzzarlapudi[2], Laxmikant Yadu[3]

[1,2,3]*Department of Civil Engineering, NIT Raipur, Chhattisgarh, India.*

[1]*Corresponding Author : gangisettisatyanandam@gmail.com*

Received: 21 May 2026 Revised: 06 July 2026 Accepted: 12 August 2026 Published: 31 August 2026

Abstract *- Estimation of seed moduli accurately are very important for conducting reliable backcalculation of layer (Bituminous, granular, subgrade) moduli using data generated by Falling Weight Deflectometer (FWD). This research presents an effective Deflection Basin Parameter (DBP)-based correlation method for predicting seed moduli of flexible pavement layers at various distress levels. FWD tests were performed on three pavements having different distress levels in different parts of India. A database consisting of 7000 pavement responses was created with the help of IIT-PAVE software by taking into account different thickness and modulus combinations of layers. Regression models were formulated in order to find out correlations between DBPs and layer moduli (M_L) of bituminous, granular, and subgrade layers. The formulated regression models were validated via backcalculation analysis using KGPBACK software and compared with the Abd El-Raof et al. (2018) technique. It was found that the proposed correlation models provided excellent prediction with the R-squared (R^2) of 0.96, 0.95, & 0.81 for bituminous, granular, and subgrade layers, respectively. Validation of the models revealed that they showed smaller RMSE of 2.4% to 9.1% as compared to 4.2% to 10.8% found by the existing method.*

Keywords *- Deflection Basin Parameters, Falling Weight Deflectometer, Flexible Pavement, Backcalculation Analysis and Seed Moduli.*

1. Introduction

Flexible pavements are exposed to constant traffic loadings and the environment, leading to gradual degradation of their physical characteristics. It is thus crucial to carry out accurate structural analysis of pavements in order to effectively manage the maintenance, rehabilitation, and overall pavement management system [1, 2]. Within the various non-destructive testing techniques, the FWD-based method has been recognized as one of the most popular methods for evaluating the structural condition of pavements based on their deflections [3]. The present investigation aims to improving the accuracy of seed modulus estimation for flexible pavement back-calculation from DBPs obtained using FWD testing.

1.1. Background and Motivation

Pavement structure is affected greatly by factors such as traffic repetition, environmental effects, aging of materials, and moisture content, leading to pavement deterioration [1]. It is essential to conduct a reliable assessment of pavement structural performance to ensure proper pavement maintenance practices [2]. In the last few decades, FWD test method has been used extensively due to its advantages over other conventional methods of pavement assessment [3]. FWD testing involves the use of pavement surface deflections caused by impact loading and the formation of a deflection basin that describes the stiffness characteristics and load transfer behavior of the pavement [4]. This test helps gain information on the integrity of the pavement structure, the stiffness of the layers, and the mode of degradation [5]. It is therefore used by some pavement authorities around the world for pavement evaluation [6]. The backcalculation method has been widely used for the determination of the moduli of pavement layers from measured deflection basins through the use of the layered elastic model and iterative calculations [7]. The backcalculation approach is highly dependent on the initial values of pavement layer moduli (M_L), known as seed moduli [4]. The selection of incorrect seed moduli frequently leads to convergence problems and produces erroneous estimates of M_L [8]. Thus, the development of methods for seed modulus estimation has emerged as a significant research topic in pavement engineering.

1.2. Challenges in Pavement Backcalculation

The process of backcalculation of M_L based on deflection basin measurements is regarded as an ill-posed inverse problem since various combinations of pavement layer characteristics can result in the same response of the deflection basin [7]. Consequently, obtaining reliable solutions to this problem is a difficult task in the analysis of pavement structure. The correctness of the obtained results largely depends on the choice of seed moduli, optimization technique, and stopping criteria [9].

The conventional approach of backcalculation usually needs several rounds to ensure that the error between the measured and calculated deflections is minimized [10]. Unrealistic assumptions in many instances can cause a local solution or a non-unique solution, as well as too much computation time [11]. In addition, the nonlinear behavior of pavement materials, changes in the environment, and errors in measurements add to the complexity of the backcalculation process [12]. Recent research emphasizes the need for reasonable seed modulus values in enhancing convergence and reducing prediction errors [13, 14]. Despite the development of advanced machine learning techniques and probabilistic models for predicting the pavement modulus, their implementation is difficult due to high computational costs and large data needs [15, 16]. It is therefore required to establish efficient methods that can produce realistic values of seed modulus.

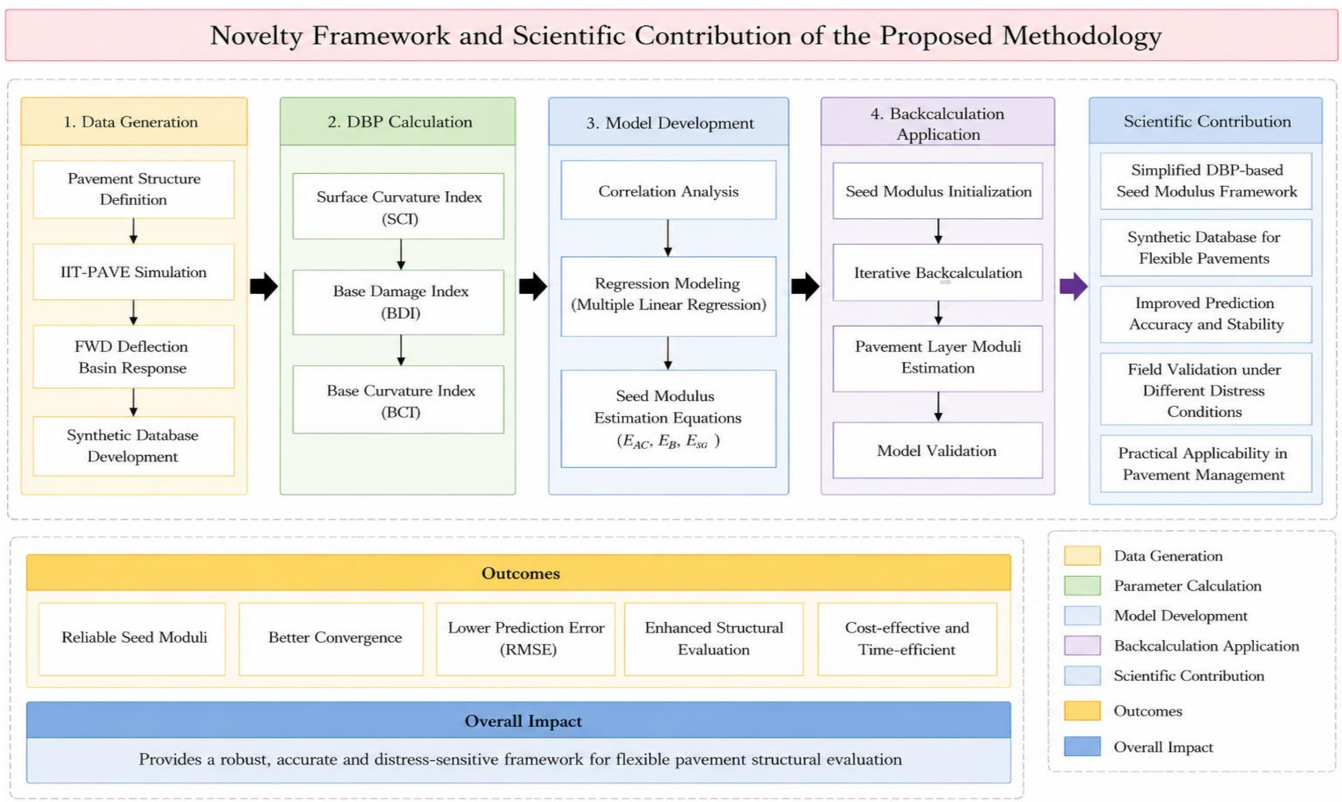


Fig. 1 Novelty framework and scientific contribution of the proposed methodology

1.3. Research Gap and Problem Identification

A number of studies have explored the application of Deflection Basin Parameters (DBPs), including SCI, BDI, and BCI for the structural assessment of pavements and prediction of moduli [11, 17]. These parameters have shown significant sensitivity to certain layers of the pavement and have proven useful in estimating the structural capacity of pavements through the use of FWD deflections [18]. Additionally, empirical models and artificial intelligence methods have been used for the correlation of DBPs and pavement M_L [13, 16]. Even so, current research efforts are confined to a particular type of pavement distress, region, or data, making them less applicable in a wider context [1, 19]. Further, currently available seed modulus prediction equations are not validated for different types of pavement distress and have exhibited inconsistent accuracy in backcalculation analysis [4]. Few studies have explored the DBP relationship in Indian flexible pavements and its effect on the convergence process in backcalculation analysis [20]. The existing research suggests that using improper seed modulus can greatly influence the iterative process convergence and the reliability of predictions in pavement backcalculation [21]. Thus, it is necessary to develop a scientifically justified DBP-based approach for determining seed modulus values of flexible pavements in different distress scenarios [22]. Despite various attempts in literature for seed modulus estimation via empirical, regression and machine learning algorithms, current techniques are developed based on small sample sizes and tested only in particular scenarios of pavement systems. This limits the application of the techniques in estimating seed modulus for other pavements with varying distress and structural states. In this paper, we seek to bridge this research gap through the development of a regression model based on DBP using a large-scale database synthesized via IIT-PAVE and field FWD tests from pavements with varying distress levels.

1.4. Research Objectives and Scope

The primary objective of the current study is to design a Deflection Basin Parameter-based approach for better seed moduli prediction in three-layer flexible pavements. To fulfill this requirement, a synthetic database was developed by using the IIT-PAVE software in order to formulate regression-based relationships between DBPs and M_L. These models were then validated by using the FWD data obtained from different pavement sections having good, fair, and poor distress. Moreover, the effectiveness of the suggested approach was investigated via backcalculation and RMSE-based validation in comparison with a seed modulus estimation model.

1.5. Original Contribution of the Research

Mainly, the significant aspect of the present study lies in the creation of a regression model based on Deflection Basin Parameter (DBP), which can be used to estimate the seed moduli of the bituminous, granular, and subgrade layers of flexible pavements that consist of three layers. Different from the existing empirical models, the proposed regression model uses a large synthetic dataset developed with IIT-PAVE, along with field measurements performed with the help of FWD on pavements that have various types of distress [19].

The rest of this paper is structured as follows. In Section 2, we summarize the current state-of-the-art on pavement backcalculation and seed modulus prediction based on the DBP approach. In Section 3, we introduce the test sections and the experimental program. In Section 4, we discuss the construction of the synthetic database, and in Section 5, we construct the regression models

2. Literature Review

Pavement Structural Condition Assessment by means of FWD testing has gained its significance as part of modern pavement management systems. Many researchers have analyzed the application of deflection basin characteristics, empirical models, mechanistic methods, and artificial intelligence algorithms for pavement layer modulus determination and backcalculation analysis [1].

However, recent progress in modeling and machine learning techniques has made pavement structural condition assessments even more accurate [2]. At the same time, problems of convergence, seed modulus determination, and distress-related validation still pose great challenges in flexible pavement backcalculation analysis.

2.1. Structural Assessment of Flexible Pavements Using FWD

Falling Weight Deflectometer (FWD) testing has been regarded as one of the most efficient non-destructive methods used to assess the structural quality of flexible pavements [3]. The FWD test applies a dynamic impulse load on the pavement surface to simulate moving wheel loads and measures the resulting deflection profile through the use of several geophones installed at varying radial distances from the load point [4]. The capacity of FWD tests to evaluate the structural condition of pavements has been well studied in different pavement structures and environmental conditions [6]. There are several studies that have confirmed that the geometry and magnitude of deflection basin are very responsive to changes in stiffness properties of pavement layers and subgrade soil [7].

The structural evaluation based on FWD measurements has thus become an important tool for pavement maintenance and rehabilitation works [8]. Experimental research has made significant progress towards better comprehension of the mechanics of pavement structures subjected to dynamic loads [9]. Some studies have focused on the use of viscoelastic theory and wave propagation theory to interpret the results of FWD tests conducted on flexible pavements [10]. Machine learning algorithms have recently proven their efficiency in predicting the deflection response of pavements [11].

2.2. Deflection Basin Parameters and Structural Interpretation

Deflection Basin Parameters (DBP) refer to indices that are simplified from FWD deflections and are often employed for pavement structure interpretation [12]. DBP refers to indices that have unique properties pertaining to the deflection basin and can offer information regarding the stiffness and condition of the pavement layers [13]. In terms of available DBP, SCI, BDI, and BCI are most frequently used to assess the pavement structure [14].

SCI is mainly linked to the stiffness of the top bituminous layer, while BDI depends on the structural state of the granular base layer [15]. Likewise, BCI is mostly affected by the subgrade behavior and pavement support state [16]. Many studies have proved that there exist high correlations between DBPs and M_L using empirical and regression models [17]. Additionally, DBPs have been found to be useful in the evaluation of pavements' structural state at the network level because of their simple calculations and applications [18]. The researchers have also focused on probabilistic and sensitivity-based techniques for assessing the reliability of DBP-based characterization techniques for structural assessment [19]. Despite the useful information about the structure provided by DBPs, their use is affected by the thickness of the pavement, climatic conditions, and loading features [20]. Hence, still, many DBP-based studies have been mostly focused on structure evaluation rather than on seed modulus estimation.

Thus, their use in improving backcalculation convergence is underexplored.

2.3. Current Approaches to Prediction of Seed Moduli

The ability to predict seed moduli with reliability is crucial for achieving stability in the pavement backcalculation process. Various methods have been suggested to predict moduli of pavement layers based on FWD deflection values [21]. Conventional methods rely on regression models, which correlate deflection values with layer characteristics. On the other hand, new research methods consider machine learning and artificial intelligence principles to achieve more reliable predictions [22]. The empirical models for seed modulus are relatively computationally inexpensive and appropriate for pavement engineering practice [19]. Nonetheless, most of these models are designed to work under certain pavement conditions and do not exhibit consistent performance under different distress conditions [11]. The artificial neural networks models are more effective in predicting the pavement condition and modulus estimation [13]. They need large amounts of data for training and computation [16]. The recent research studies have concentrated on the development of simple DBP-based models that can enhance the convergence stability of backcalculations and minimize computational uncertainties [4]. They have presented regression-based equations to estimate the modulus of the pavement layers based on the DBPs estimated by FWD testing [11]. Similarly, other authors have provided a simple closed-form solution to estimate the moduli of pavement layers on a network level using FWD deflections [19]. These models are very useful; Furthermore, most of the regression models have been developed using small samples of pavements and have not been tested across different pavement distress situations.

Table 1. Comparative analysis of previous seed modulus prediction models

S.No.	Study	Approach	Database Type	Validation Method	RMSE / Accuracy	Major Limitation
1	Rocha et al. [4]	Layered elastic backcalculation	Field FWD data	Iterative deflection matching	Moderate prediction accuracy	Highly dependent on initial seed modulus
2	Hamidi et al. [5]	Sensitivity-based backcalculation	Pavement response database	Sensitivity analysis	Variable convergence behavior	Non-unique modulus solutions
3	Abd El-Raof et al. [19]	Empirical DBP model	FWD deflection data	Deflection comparison	Acceptable RMSE	Limited distress-condition validation
4	Wang et al. [3]	ANN-based prediction model	Airfield pavement database	ANN validation	Improved prediction accuracy	High computational complexity
5	Rocha et al. [11]	Regression-based DBP model	Synthetic pavement database	Statistical validation	Strong DBP correlation	Limited field verification
6	Present Study	Layer-specific DBP-based regression framework	Comprehensive IIT-PAVE synthetic database and field FWD data	RMSE-based validation under multiple pavement distress conditions	Lower RMSE, improved convergence, and higher prediction accuracy	Requires validation using larger pavement databases

As can be seen from Table 1, most current seed modulus estimation techniques have been developed based on small field databases or pavement types and then evaluated under constrained working conditions. In turn, the proposed approach is based on combining a broad IIT-PAVE synthetic database with field FWD tests performed on various pavement distress states.

In addition, the proposed DBP regression models for each pavement layer allow providing more accurate seed modulus initialization, faster convergence during backcalculation, and smaller RMSE compared to the benchmark technique [19].

2.4. Backcalculation Theory and Computation Techniques

Backcalculation technique is an inverse analysis method that is applied for determining the layer (Bituminous, Granular, Subgrade) moduli from measured deflection basins [6]. Generally, backcalculation entails the use of layered elastic analysis, iteration processes, and convergence techniques to minimize the discrepancy between the measured and computed pavement behavior [7]. Because of the ill-posedness and nonlinearity of the inverse problem, several sets of M_L may give rise to the same deflection basin response [5]. There are various computational strategies for enhancing the robustness and accuracy of pavement back calculation process [10]. Traditional strategies usually make use of iterative optimization techniques coupled with layered elastic analysis for estimation of pavement layer properties [17]. In recent times, techniques such as viscoelastic analysis, probabilistic modeling, and deep learning techniques have been developed [22]. Despite these improvements, however, the issues of convergence stability and seed modulus assumption have continued to pose considerable difficulties in backcalculation analysis of pavements [4]. Some studies have shown that the use of an incorrect seed modulus can result in erroneous modulus estimation, increasing prediction errors [21]. It is thus imperative that rational methods of seed modulus estimation be developed.

2.5. Research Requirements and Knowledge Gap

Based on the literature review, it can be seen that extensive research has already been done in relation to FWD-based pavement evaluation, DBP analysis, and backcalculation techniques. Nevertheless, there are some limitations that remain in existing methods for predicting pavement moduli. First of all, most of the research conducted is based on localized data and only validated under certain conditions of pavement or climate [1]. In addition, few studies have focused on the effect of different pavement distress on seed modulus calculation and backcalculation convergence [18]. The machine learning algorithms and computational methods need large data sets along with computing power, which makes their application in pavement assessment very difficult [16]. Another point is that most empirical models have proven to be erratic in their performance in the field because of differences in pavement construction and environment [11]. Finally, little work has been done on the DBP relationship and seed modulus of Indian flexible pavements [20].

It can be seen from the literature that while a lot of advancements have been achieved in pavement backcalculation and DBP-driven structural evaluation of pavements, there are certain research voids that still exist in this area. This is because the methods used to develop these models are usually based on small data sets, where the validation process is done only on pavement conditions, without considering the effects of varying distress level on the seed modulus calculation. In addition, very little work exists on the use of simulation databases combined with field FWD measurements to develop regression models. Based on the literature review, the conclusion can be made that an effective seed modulus estimation framework that would be both accurate and computationally efficient, as well as distress sensitive, has not been developed yet.

3. Materials and Experimental Program

In this section, the field investigation procedure, pavement properties, and the methods of data acquisition using FWD are described. For the current study, three flexible pavement sections with varying distress levels were chosen from diverse locations across India to examine the feasibility of the developed seed modulus estimation method. Further details about the configuration of the pavements, FWD testing arrangement, and parameters used in the experiments are provided in the subsequent sub-sections.

3.1. Description of Study Sections

Three flexible pavement sections from various geographic locations of India have been chosen for the present study. The chosen pavement sections have different levels of distress, such as good, fair, and poor distress levels, in order to assess the effectiveness of the proposed DBP-based seed modulus estimation method under different structural conditions.

The chosen sections consist of three-layered flexible pavements that include bituminous, granular, and subgrade layers. Pavement Section 1 (PS-1) is located in the eastern coastal area of India and constitutes a pavement section that shows relatively better structural condition with lesser surface distress severity.

Pavement Section 2 (PS-2), which is located in the southern interior area, showed relatively greater structural deterioration and distress severity. Pavement Section 3 (PS-3), which is located in the central-southern part of India, is a pavement section that shows moderate or fair distress condition. The selected pavement sections have been chosen to make sure that there is some variability among pavement sections in terms of pavement performance, structural features, and distress severity. Such variability is critical in order to examine the efficiency of the proposed seed modulus estimation approach.

Table 2. Details of selected pavement sections

Pavement section	Length (km)	Layer average thickness (mm)		Number of deflection basins	Distress condition
		Bituminous	Granular		
1	50	180	450	100	Good
2	9	165	450	90	Poor
3	19	150	450	95	Fair

3.2. FWD Test Program

The FWD test was carried out on all selected study sections with the aim of assessing their structural behavior when subjected to dynamic loading similar to a moving vehicular load. The FWD test was performed using a KUAB-type vehicle mounted instrument with seven geophones installed to measure pavement responses at various radial distances from the center point of load application. For the purpose of testing, an impulse load of about 40 kN was introduced by means of a circular loading plate of 150 mm radius. Pavement surface deflections caused by the impulse load were then determined through geophones placed at certain offsets from the center of the loading plate. The collected deflection basins were further used to compute the Deflection Basin Parameters (DBPs), determine seed moduli, and conduct backcalculation. A total number of 285 deflection basins were obtained from the pavement test sections chosen. Before any analysis could be conducted, the measured data were subjected to screening to determine representative homogeneous pavement sections that could be used for structural evaluation. This measured FWD data formed the basic input data for the proposed framework.

Table 3. FWD testing configuration

S.No.	Parameter	Value
1	Applied Load	40 kN
2	Plate Radius	150 mm
3	Number of Geophones	7
4	Number of Deflection Basins	285
5	Pavement Type	Three-layer flexible pavement
6	FWD Equipment	KUAB FWD System

4. Development of Synthetic Database

The present work involved the development of an extensive synthetic database in order to determine the reliable functional relationships between DBPs and the moduli of pavement layers in the case of three-layered flexible pavements. The synthetic database was created through the use of the IIT-PAVE software by varying the layer thickness (h_L) and modulus of typical Indian flexible pavements. The created database was then used for modeling and seed modulus prediction. Further details on the simulation procedure and assumptions are provided below.

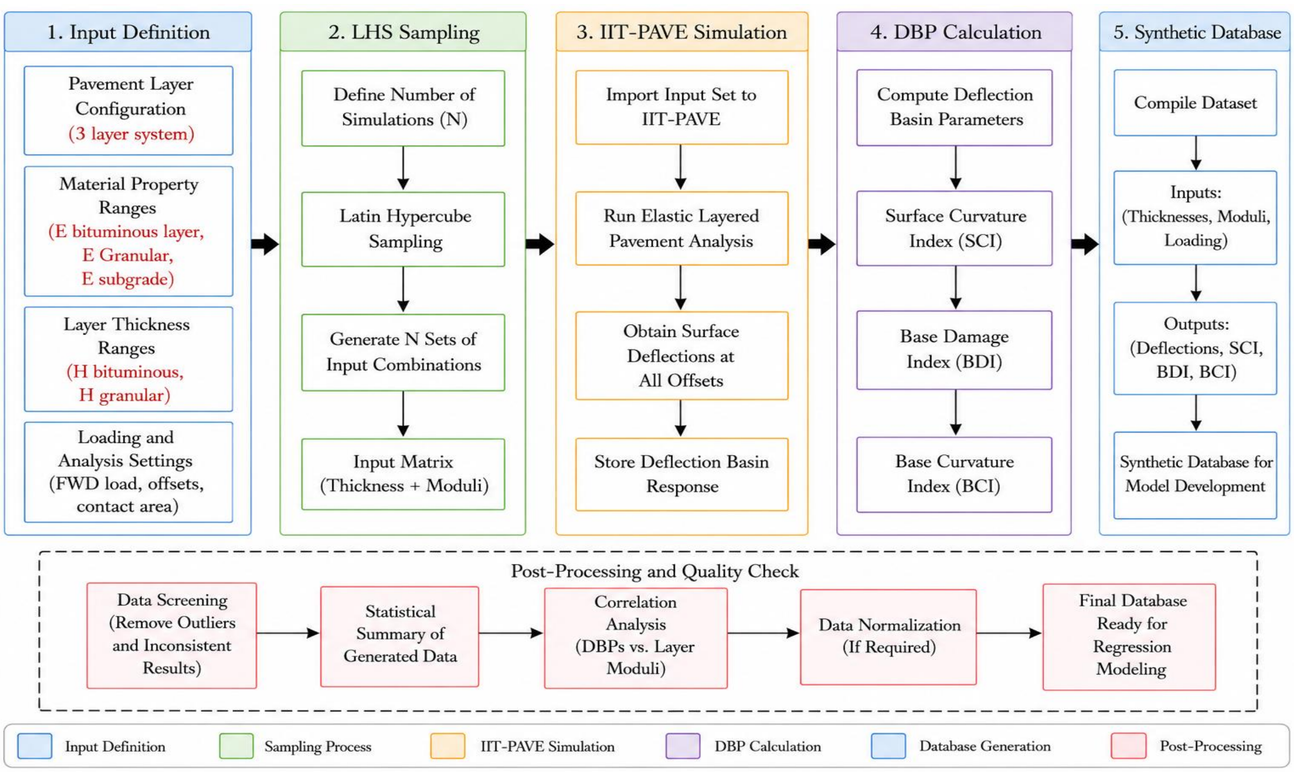


Fig. 2 IIT-PAVE simulation and synthetic database generation workflow

4.1. IIT-PAVE Simulation System

The artificial database of the pavement response is created through the use of IIT-PAVE software that utilizes the concept of a multilayer elastic system. The simulation of pavement deflection due to wheel loads depends upon the inputs of pavement h_L, modulus of elasticity, Poisson's ratio, and the load condition. In the current research work, IIT-PAVE simulation is done for different combinations of pavement structures.

A total of 7000 responses of artificial pavements were created using the variation of the Bituminous Layer Modulus (BLM), Granular Layer Modulus (GLM), and Subgrade Modulus (SGM), and thickness of the pavement layers. For all type of pavement combinations, surface deflections for various radial distances from the point of load application were calculated. The simulated deflection curves were then used for the calculation of DBPs, such as Surface Curvature Index (SCI), Base Damage Index (BDI), and Base Curvature Index (BCI). This database was employed in developing regression relations between DBPs and moduli of pavement layers. By using the artificial database, pavement performance under different combinations of M_L could be evaluated systematically

4.2. Choice of h_L and Modulus Values

The values of h_L and ranges of elastic moduli used in the simulation framework were chosen considering the usual pavement structures found in India. The ranges chosen were expected to reflect realistic conditions corresponding to different levels of pavement structure strength and distress. Various combinations of thicknesses of bituminous layers, granular layers, and M_L were considered to cover all possible scenarios related to pavement structural behavior. The ranges of elastic moduli chosen for simulation included a broad range of conditions related to the strengths of pavement materials, ranging from weak to stiff pavement layers. Similarly, the ranges of h_L chosen reflected common design practices in relation to medium and heavy-traffic pavements. This helped in generating a realistic set of data for building the seed modulus prediction models using DBP.

Table 4. Range of pavement layer properties used in simulation

Pavement Layer	Thickness Range (mm)	Elastic Modulus Range (MPa)	Poisson's Ratio
Bituminous Layer	80 to 200	500 to 6000	0.35
Granular Layer	300 to 500	50 to 600	0.4
Subgrade Layer	Semi-infinite	30to 150	0.45

4.3. Simulation Assumptions and Boundary Conditions

The layered elastic analysis conducted by the use of IIT-PAVE computer program was done based on some simplifying assumptions that are generally made in pavement structure analysis. The pavement structure was assumed to be a multilayered elastic medium where each layer is homogeneous, isotropic, and linearly elastic. Full bonding was assumed between the adjacent pavement layers to allow continuity of stresses and deformations between them. The wheel load was simulated as a circular uniform load on the pavement surface through a rigid loading plate. A static loading condition was assumed for the generation of pavement responses. Semi-infinity assumption was made for the lowermost subgrade layer in order to simulate realistic field conditions. The selected assumptions enabled the quick evaluation of pavement surface deformations in a number of pavement structures. While real pavements have nonlinear and viscoelastic behavior in field applications, the selected assumptions give reasonable approximations in the analysis of mechanistic pavement structures and are extensively applied in pavement backcalculation procedures. The created synthetic database thus gives a reliable basis for developing practical seed modulus prediction models based on DBP approach.

Table 5. Assumptions adopted in layered elastic analysis

S.No.	Assumption	Description
1	Material Behavior	Linear elastic
2	Layer Characteristics	Homogeneous and isotropic
3	Interface Condition	Fully bonded layers
4	Loading Condition	Static circular load
5	Load Distribution	Uniform pressure distribution
6	Subgrade Condition	Semi-infinite layer
7	Analysis Type	Multilayer elastic analysis
8	Deformation Assumption	Small deformation theory

5. DBP Based Seed Modulus Models Development

A pavement response database obtained through the use of IIT-PAVE software package was used to develop a practical correlation between Deflection Basin Parameters (DBPs) and moduli of layers in three-layer flexible pavement systems. Regression analysis techniques were employed to derive an equation that could be used to predict bituminous, granular, and subgrade M_L based on DBPs calculated from virtual FWD deflection basins. These models were meant to generate realistic values of seed modulus for improving the convergence of pavement backcalculation process.

5.1. Selection of Important Deflection Basin Parameters

The selection of important DBP was done keeping in view the sensitivity of these parameters toward various pavement layers, as well as the ability of these parameters to describe the structural properties of flexible pavements. In the current research, the deflection basin parameters used are SCI, BDI, BCI, and radial deflections at various offsets from the loading point.

The selection of SCI for the characterization of the bituminous layer was due to its high sensitivity towards near-surface pavement stiffness changes. Likewise, BDI was used for analysis of structural performance of granular layer because of its sensitivity towards intermediate pavement layers. On the other hand, BCI and far offset deflections were used for characterization of the subgrade and lower pavement layers. The selected DBPs were correlated with the M_L using statistical and regression methods. The aim was to find out the most significant DBPs that control the pavement structural response and then use them to develop rational seed modulus prediction models.

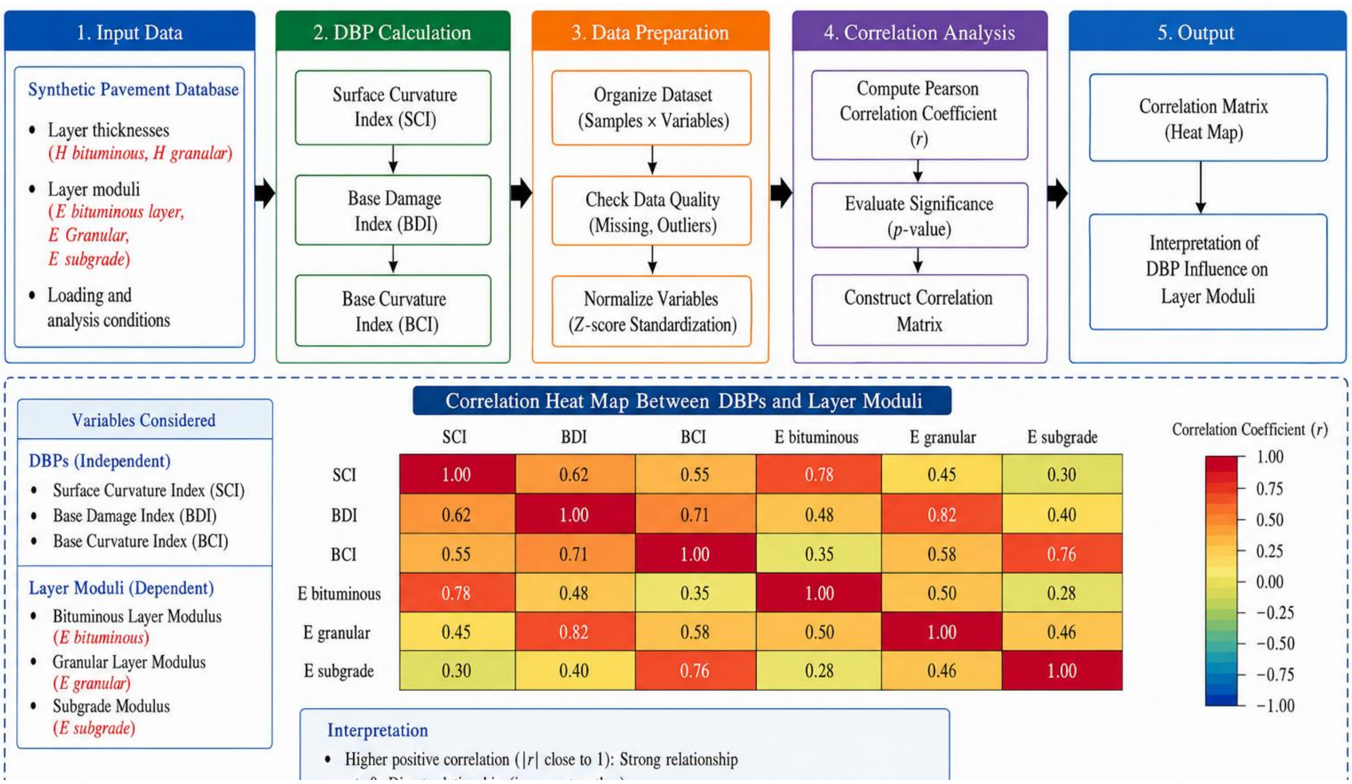


Fig. 3 Correlation heat map between DBPs and pavement layer moduli

5.2. Development of Regression-based Models

Regression analysis was done using the artificially generated database for development of mathematical equations between the DBP and modulus of the pavement layers. The regression models were separately derived for bituminous, granular, and subgrade layers using different combinations of DBPs and pavement h_L as predictors. Logarithmic transformation of variables was done to stabilize the regressions and improve prediction accuracy. The regression models were derived by testing different combinations of predictor variables and their effects on the coefficient of determination (R^2) and prediction errors. The final regression equations were chosen based on their statistical significance and prediction accuracy. The models were developed in an attempt to make them computationally simple but still accurate enough. The application of regression techniques made possible the formulation of seed modulus prediction models that were computationally simple and efficient enough for field use. These equations will also aid in speeding up the process of initializing the M_L values in the backcalculation procedure.

5.3. Development of Correlation Equations

The regression analysis, individual correlation equations have been derived for the prediction of moduli of bituminous, granular, and subgrade pavement layers. The correlation equations thus developed utilize the important DBPs along with the thicknesses of different pavement layers as independent parameters for determining the stiffness characteristics of pavement layers. The correlation equation for the bituminous layer showed high dependency on SCI and near offset deflections owing to the sensitivity of upper pavement layers to the surface curvature characteristics. In a similar manner, the granular layer showed high dependency on BDI and intermediate offset deflections, while the subgrade layer showed high dependency on BCI and far offset deflection values. The correlation equations developed offer rational predictions of the modulus values of pavement layers under various pavement structural conditions and may be used as seed moduli in pavement backcalculation analysis.

Given:

- MRB = Modulus of bituminous layer (MPa)
- MRG = Modulus of granular layer (MPa)
- MRS = Modulus of subgrade (MPa)
- HB = Thickness of bituminous layer (mm)
- HG = Thickness of granular layer (mm)

Table 6. Developed DBP-based regression equations for pavement layer moduli

Eq. No.	Pavement Layer	Developed Regression Equation	R^2
Equation (1)	Bituminous Layer	$\log(MRB) = -0.74 \log(HB) + 5.4 \log(SCI) + 6.31 \log(R200) - 55.56$	0.96
Equation (2)	Granular Layer	$\log(MRG) = -1.62 \log(HG) - 1.79 \log(BDI) - 0.502 \log(R450) + 17.72$	0.95
Equation (3)	Subgrade Layer	$\log(MRS) = -0.42 \log(BCI) - 0.08 \log(R900) - 0.035 \log(R1200) + 7.056$	0.81

5.4. Statistical Performance Evaluation of Developed Regression Models

Further assessment of the predictive power of the developed regression models was carried out through scatter plots of predictions versus simulations. Figures 4(a), 4(b), and 4(c) show the predicted and simulated modulus for the bituminous layer, granular layer, and subgrade, respectively. The reference line in each figure shows perfect agreement between the predicted and simulated results. The bituminous and granular models demonstrated perfect agreement, with R^2 of 0.96 and 0.95, respectively, while the subgrade model had relatively lower but still acceptable agreement, with R^2 of 0.81.

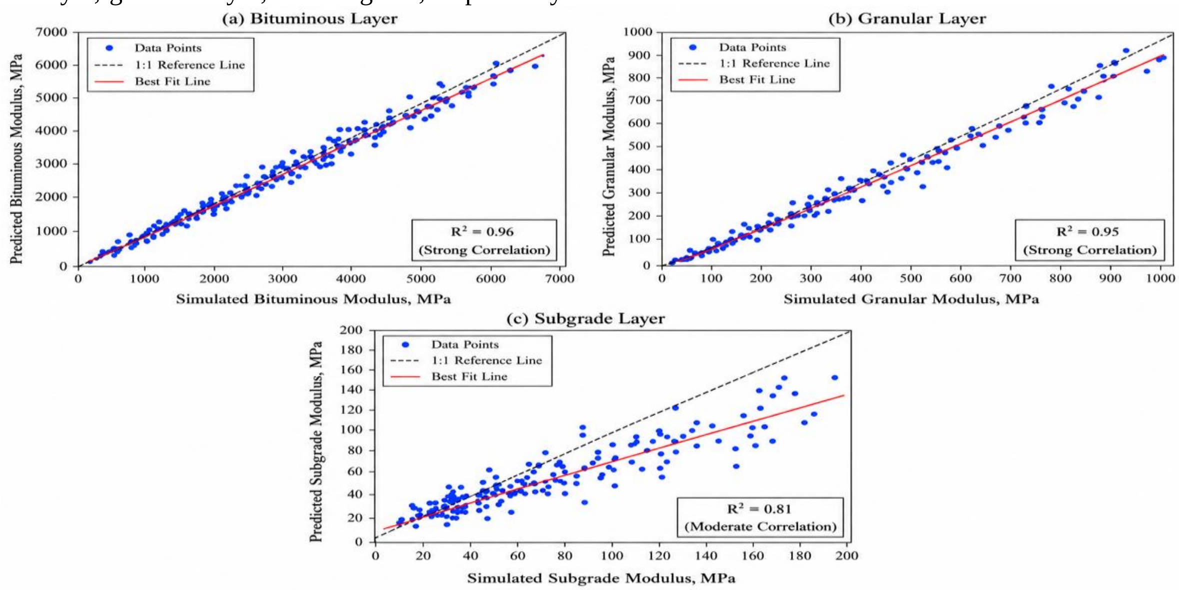


Fig. 4 Predicted-versus-simulated modulus values for the developed DBP-based regression models: (a) bituminous layer, (b) granular layer, and (c) subgrade layer

Table 7. Statistical performance indicators of developed regression models

S.No.	Parameter	Bituminous Layer	Granular Layer	Subgrade Layer
1	Coefficient of Determination (R^2)	0.96	0.95	0.81
2	Prediction Accuracy	Excellent	Excellent	Good

3	Correlation Strength	Very Strong	Very Strong	Strong
4	Model Reliability	High	High	Moderate

6. Backcalculation Analysis

The seed modulus models based on the Deflection Basin Parameters (DBPs) had been formulated, the developed models were then applied in pavement backcalculation analysis in order to investigate the effectiveness of the models and prediction capabilities under different distress levels of pavements. Backcalculation analysis was done using the KGPBACK software based on field measurements of FWD deflection basins of the selected pavements. The main aim of the backcalculation analysis was to determine realistic values of M_L and the effect of seed modulus initialization on convergence and prediction.

6.1. KGPBACK Backcalculation Approach

Backcalculation computations are performed employing the KGPBACK computer program, which has been developed on the basis of MET and an iterative optimization approach. KGPBACK computes the values of M_L through employing the concept of minimum deflection discrepancy between calculated and measured pavements. In the present study, the measured deflection basin data obtained with the help of FWD was employed as input data for backcalculation computations. The approach entails successive adjustment of values of pavement layers' modulus until the difference between calculated and measured deflection basin becomes minimum. This optimization process was controlled by the criterion of minimum root mean square error (RMSE). The pavement structure was assumed to have a three-layered flexible pavement structure made up of bituminous, granular, and subgrade layers. The measured thicknesses of each layer obtained from field investigations were considered as fixed input data in the analysis. The seed moduli values determined using the DBP approach were used as initial input data.

6.2. Initialization of Seed Modulus Values Using Proposed and Existing Models

The initial seed modulus values needed for backcalculation were calculated using the proposed DBP-based regression models and the existing model by Abd El-Raof et al. The reason for employing two different methods for seed modulus initialization was to assess the effect of seed modulus selection on backcalculation and prediction accuracy. In the case of the proposed method, the derived regression models were used to calculate the initial seed modulus values of the bituminous, granular, and subgrade layers based on the DBP obtained from FWD measurements. The seed moduli calculated indicated the structural condition and distress of the chosen sections of pavements. Similarly, the seed moduli values were calculated using the existing empirical models developed by Abd El-Raof et al. The seed moduli were then used as input parameters during backcalculation.

Table 8. Comparison of seed moduli obtained from developed and existing models

S.No.	Pavement Layer	Developed Model Range (MPa)	Existing Model Range (MPa)
1	Bituminous Layer	451 to 5992	855 to 6608
2	Granular Layer	72 to 543	45 to 980
3	Subgrade Layer	82 to 101	80 to 136

6.2.1. Existing Abd El-Raof et al. (2018) Seed Modulus Model

Abd El-Raof et al. (2018) model (Existed Model)

Abd El-Raof proposed a set of equations to determine the coefficients a1, a2. These coefficients are then used to estimate the M_L of the bituminous and granular layers, while a separate equation is suggested for evaluating the subgrade layer modulus.

$$a_1 = \frac{4.056 \times SIP^{-0.407} \times H_P^{0.546} + 0.006 \times A_2^{2.443}}{0.203 \times D_1} \quad (4)$$

$$a_2 = 0.249 \times (\log E_B) - 0.977 \quad (5)$$

$$a_1 D_1 + a_2 D_2 = SN_{eff} \quad (6)$$

$$E_{SG} = -346 + 0.00676 \times \left(\frac{2P}{D_{36} + D_{48}}\right) \quad (7)$$

Where a_1 and a_2 are the structural layer coefficients of the AC and base layers; SIP is structural index of the pavement; H_p is the pavement thickness (in mm); A_2 is a deflection basin parameter represent middle layer condition; D_1 and D_2 are the thicknesses (in inches) of the AC and base layers; EB is the base layer modulus; SNeff is the effective structural number (in inches); ESG is the subgrade modulus; P is the applied load (in pounds); and D_{36} and D_{48} are the measured deflections at distances of 36 and 48 inches from the load plate.

E_{AC} was directly calculated from the AASHTO 1993 chart (AASHTO 1993) using the coefficient a1 obtained from Equation (4). Subsequently, the base layer modulus (E_B) was calculated and using Equations (5) & (6) and E_{SG} is determined by using Equation (7). Further, the moduli values obtained from these equations were used as seed moduli for backcalculation analysis. For the bituminous layer, the highest seed modulus 6608 MPa and lowest value 855 MPa. Similarly, for the granular layer, maximum and minimum values of 980 MPa and 45 MPa, respectively. For the subgrade layer, the minimum value 80 MPa and the maximum value 136 MPa.

6.2.2. Proposed DBP-Based Seed Modulus Framework

The DBP-based seed modulus estimation approach is based on the derived regression equations (see Equations (1)-(3) in Section 5.3) to find initial modulus values of bituminous, granular and subgrade layers according to the obtained Deflection Basin Parameters (DBPs) and thicknesses of pavement layers.

Unlike the current empirical approach, the proposed DBP-based seed modulus framework allows obtaining the relationships between DBPs and pavement layer moduli, and, therefore, provides better initialization of the backcalculation procedure.

The DBPs were calculated from the FWD measured deflection basins, while the thicknesses of pavement layers were determined during field investigation. Afterward, the obtained inputs were substituted into the proposed regression equations to obtain seed modulus values of each pavement layer. Finally, the estimated seed modulus values were used as an initial value of backcalculation process in the KGPBACK software package.

The proposed framework was validated by the measured FWD data from pavement sections with different levels of distress: good, fair and poor. The obtained seed moduli provided higher convergence of backcalculation procedure and lower values of RMSE than that of the benchmark model by Abd El-Raof et al. (2018).

6.3. Convergence Behavior of the Backcalculation Process

The convergence behavior of the backcalculation process was investigated based on the iterative decrease in errors between measured and predicted deflections. The iterative backcalculation procedure was performed until the error between measured and predicted deflections met the set convergence criteria.

The developed DBP-based seed modulus approach exhibited good convergence behavior during the backcalculation process for all pavement sections tested. The seed moduli obtained from the developed regression models led to better convergence behavior compared to the conventional empirical method. This could be due to the close relationship between selected DBP and pavement layers' structural properties.

A total of 232 representative deflection basins were analyzed using backcalculation techniques depending on the distress levels of the pavements. The pavement M_L obtained from the backcalculation analysis reflected realistic pavement behavior, as expected from the pavements under distress. Pavement sections with severe distress exhibited relatively low values of pavement layer stiffness, while those in good condition had high structural stiffness and low deflection. Based on comparative analysis, it can be seen that the proposed methodology generated lower RMSE values and better correlation between the measured and predicted deflection basins. This clearly shows the applicability of the DBP methodology in estimating rational seed modulus and performing backcalculation analysis.

7. Results and Discussion

The proposed DBP based seed modulus approach was validated using experimental FWD data obtained from pavements experiencing various distress states. The efficacy of the proposed approach was determined based on the comparison of predicted seed moduli, back-calculated M_L, and RMSE between experimentally measured and calculated pavement deflections.

The results produced by the proposed approach were compared with those of the existing approach for determining the accuracy and convergence behavior of the predictions.

7.1. Properties of FWD Deflection Basins for Various Distress Situations

The FWD deflection basins recorded varied results across the chosen pavement sections owing to variations in pavement structural condition, stiffness of the layers, and distress level.

The FWD deflection basins recorded for pavement section PS-1, which is characterized by good pavement structural condition, had relatively lower surface deflections and flat deflection basin profiles. On the other hand, pavement section PS-2 had high deflection magnitudes and steep deflection basin profiles.

The reaction of the deflection basin of Pavement Section PS-3 is an indication of its intermediate behavior between Pavement Sections PS-1 and PS-2. It means that the pavement is structurally moderate and functionally good.

The variations in the parameters of the deflection basin have clearly brought out how the condition of pavement distress affects structural behavior and, hence, the importance of estimating seed modulus using methods that consider the distress condition of the pavements.

It was observed that the near-offset deflections are more sensitive to the stiffness of the upper pavement layers, while the far-offset deflections are more sensitive to the stiffness of the subgrade.

Deflections were found to be smaller and basin profiles less curved in pavement section PS-1, implying that this pavement is stiffer than the others. However, PS-2 has larger deflections and more curved basins because of the poor state of its structure. On the other hand, the reaction of PS-3 pavement falls between those of sections PS-1 and PS-2.

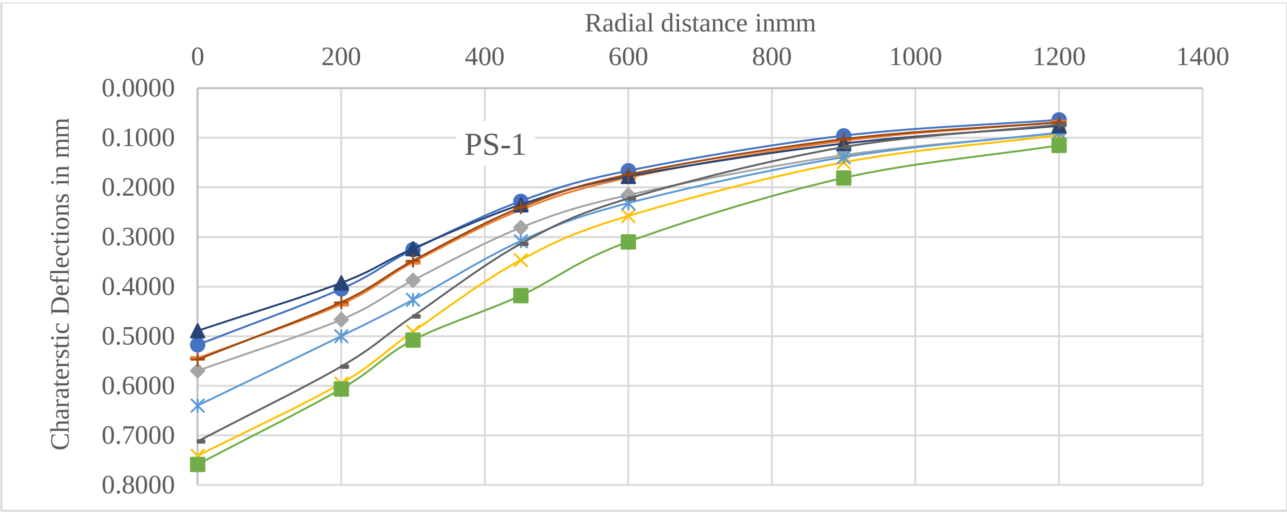


Fig. 5(a) Characteristic deflections for PS-1

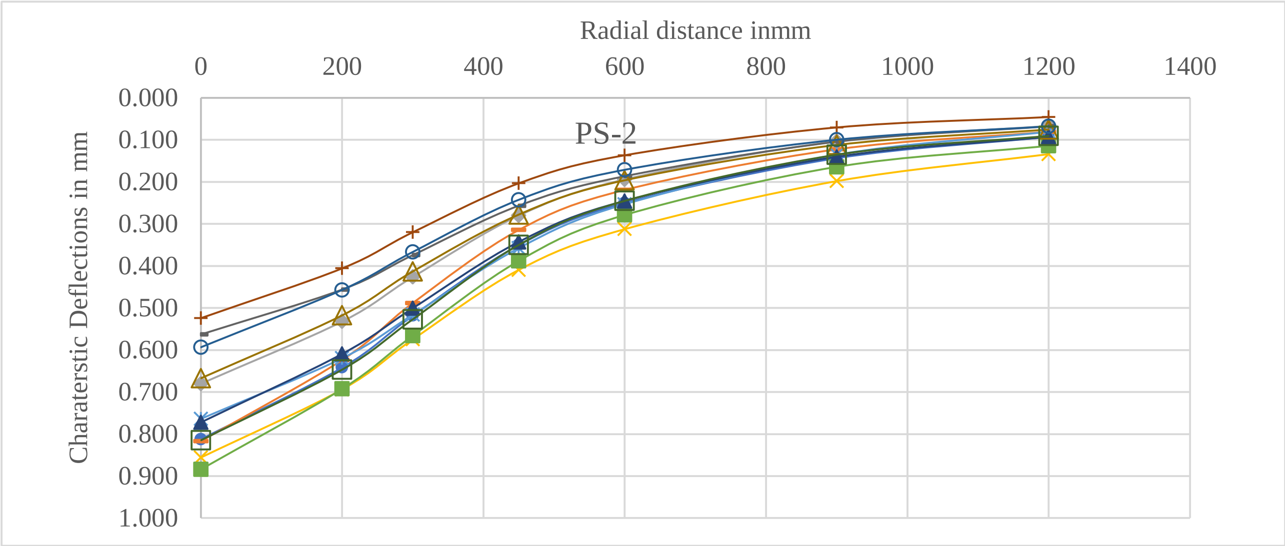


Fig. 5 (b) Characteristic deflections for PS-2

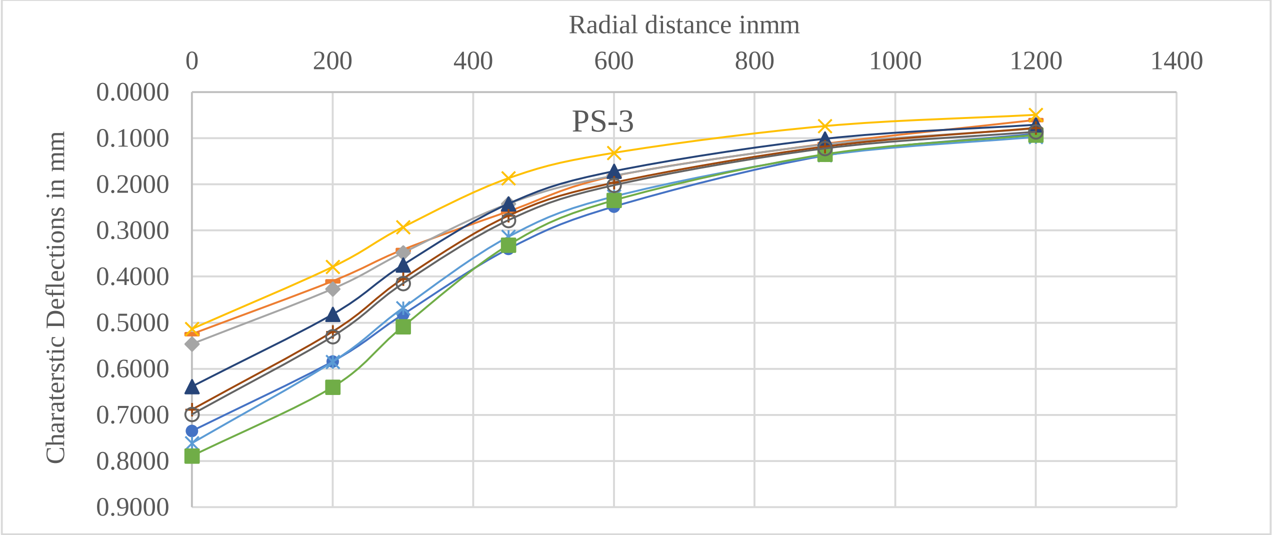


Fig. 5 (c) Characteristic deflections for PS-3.

7.2. Comparison and Evaluation of Seed Moduli

The seed moduli obtained through the suggested DBP-based regression model showed variation that was realistic and in accordance with the structural state of the pavements. The pavements which had good structural condition gave comparatively high values of seed moduli for both bituminous and granular layers, whereas the pavements that had a distressed structural condition gave low values of seed moduli. The suggested framework provided bituminous layer seed moduli values in the range of 451 MPa to 5992 MPa.

This regression model produced estimates of bituminous seed modulus varying between 451 MPa and 5992 MPa. It is important to acknowledge the fact that this model has produced one prediction value, which is slightly below the calibration value of 500 MPa, which was used during the calibration process. This can be seen as a small extrapolation beyond the calibrated limits of the regression model. While the estimate generated is physically plausible for pavements in bad condition, it is also true that regression models have larger uncertainty when they are applied beyond the range of the calibration set. Therefore, predictions below the lower calibration limit need to be treated with caution, while the granular layer seed moduli values were in the range of 72 MPa to 543 MPa. Seed subgrade modulus values obtained through the suggested framework were in the range of 82 MPa to 101 MPa. In contrast, the empirical model already developed showed greater variation in the modulus values and prediction inconsistency for sections with distressed pavements. The differences imply that the new DBP-based approach is more rational in initializing the pavement layers' moduli in the process of backcalculation.

7.3. Backcalculated Moduli of Pavement Layers

The analysis of the backcalculated moduli of pavement layers based on the proposed seed modulus approach yielded values that were in accordance with the structural condition of the selected pavement sections. It was found that pavement section PS-1 had relatively high backcalculated moduli of the bituminous and granular layers, implying that there was an improvement in structural performance and load-carrying ability. On the other hand, pavement section PS-2 showed relatively low moduli of the pavement layers because of severe structural deterioration.

Maximum backcalculated moduli of 5961 MPa, 604 MPa, and 146 MPa were obtained for the bituminous, granular, and subgrade layers, respectively. Meanwhile, the minimum backcalculated moduli were 541 MPa for the bituminous layer, 72 MPa for the granular layer, and 78 MPa for the subgrade layer. These results show the effects of pavement distress conditions on structural characteristics. Furthermore, it is evident that the proposed framework provides better consistency in predicting M_L compared with the empirical approach.

Table 9. Backcalculated modulus ranges for selected pavement sections

S.No.	Pavement Layer	Minimum	Maximum
1	Bituminous Layer	541	5961
2	Granular Layer	72	604
3	Subgrade Layer	78	146

7.4. Validation based on RMSE Analysis

The effectiveness and practicality of the proposed DBP-based approach have been assessed through RMSE analysis between measured and predicted pavement deflections. The smaller the RMSE values, the closer the deflection basins measured and calculated are; hence, higher the prediction precision. Comparatively lower RMSE values were obtained by the proposed framework for all tested pavements compared to those obtained from the existing empirical model.

The RMSE values for pavement sections having good, fair, and poor distress were 2.4% to 9.1% for the proposed framework and 4.2% to 10.8% for the existing model. The lower RMSE values imply higher convergence stability and realistic initialization of M_L during backcalculation analysis. This indicates that the proposed framework is effective in predicting the deflections under different pavement distress conditions. The RMSE values obtained for both methods fall within acceptable limits from earlier backcalculation studies.

The high performance exhibited by the proposed DBP-based framework when compared to Abd El-Raof et al.'s (2018) baseline model can be explained by three main reasons. First, the regression models have been developed using a synthetic database generated by IIT-PAVE simulations, which ensures the use of a wide range of combinations of thicknesses and moduli of pavement layers, enhancing the generalization capacity of the models. Second, layer-based Deflection Basin Parameters (SCI, BDI, and BCI) have been used in the model according to their influence on the properties of bituminous, granular, and subgrade layers, making the seed modulus estimates more realistic. Third, the created models were validated using field FWD data from pavements showing different levels of distress, which provided practical usability of the models. All of these resulted in a better convergence of backcalculation and the model RMSE values compared to the existing empirical model.As compared to the seed modulus estimation techniques already documented in literature, the proposed method provides the following three salient advantages: (i) layer-wise regression equations based on physically meaningful Deflection Basin Parameters; (ii) calibration based on a synthetic database, which has been developed comprehensively and validation of the method based on the results of field FWD tests conducted on pavements in various distress stages; and (iii) better initialization of the seed modulus values, thereby leading to better back calculation and reduced RMSE.

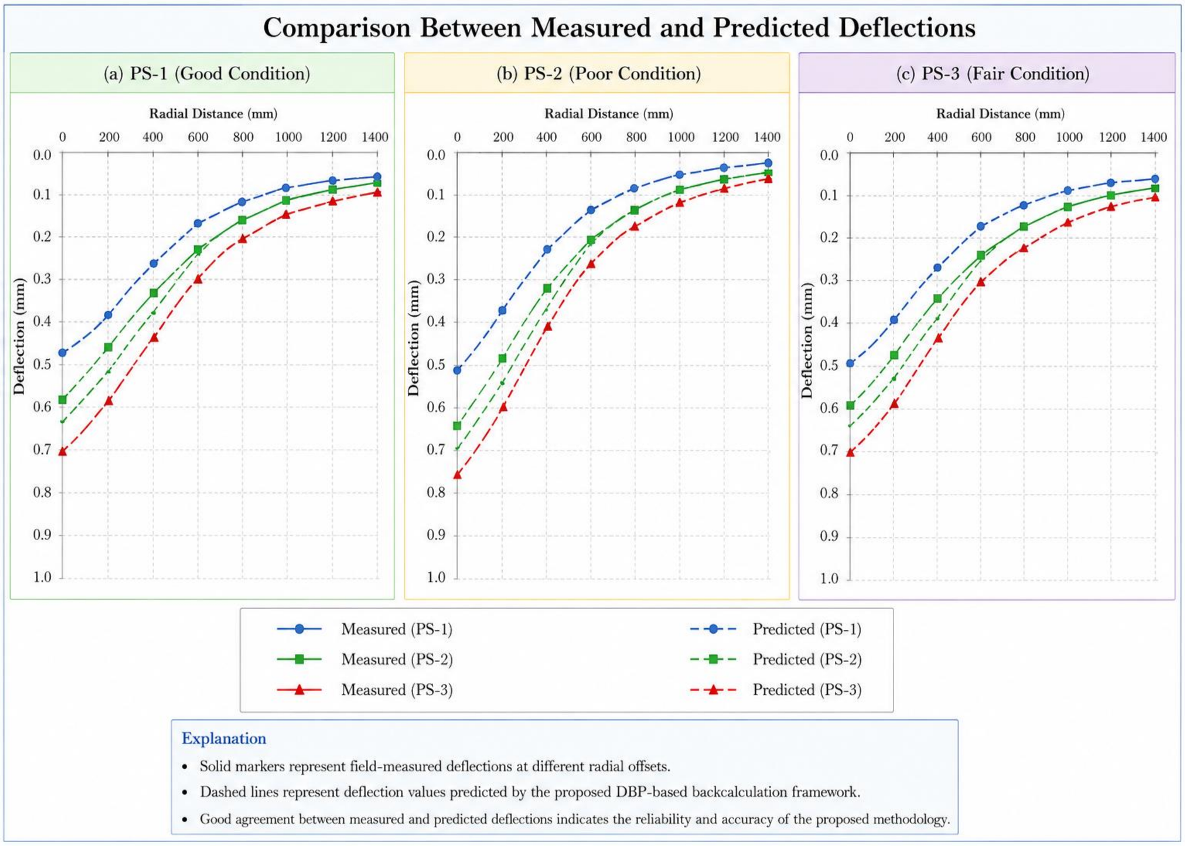
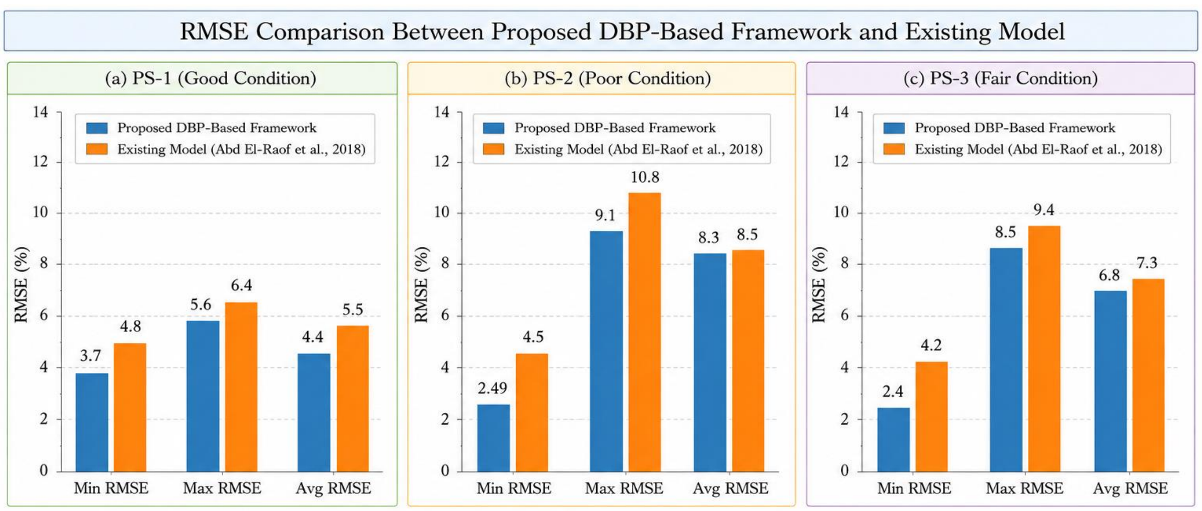


Fig. 6 RMSE comparison between proposed and existing approaches



Summary of Average RMSE (%)

Pavement Section	Distress Condition	Average RMSE (%): Proposed DBP-Based Framework	Average RMSE (%): Existing Model (Abd El-Raof et al., 2018)
PS-1	Good	4.4	5.5
PS-2	Poor	8.3	8.5
PS-3	Fair	6.8	7.3

Fig. 7 RMSE comparison between proposed and existing approaches

Table 10. RMSE of Predicted and Measured Deflections for Selected Pavement Sections

Study Section	Seed Moduli from Pavement Stretch Distress Conditions	RMSE %					
		Developed Model			Abd El-Raof et al.		
		Min	Max	Avg	Min	Max	Avg
PS-1	Good	3.7	5.6	4.4	4.8	6.4	5.5
PS-2	Poor	2.49	9.1	8.3	4.5	10.8	8.5
PS-3	Fair	2.4	8.5	6.8	4.2	9.4	7.3

7.5. Engineering Applications of the Seed Modulus Framework Based on DBP

The developed seed modulus framework based on DBP is a relatively easy and efficient way to evaluate pavement structure and conduct backcalculation analysis. The use of the suggested method allows increasing the efficiency of seed modulus initialization and reducing convergence uncertainty typical of conventional approaches based on empirical data. The methodology may be efficiently applied for evaluating pavement structure at the network level, making decisions about maintenance priorities and rehabilitation measures.

In addition, the ability of the developed methodology to estimate pavement modulus under different levels of distress makes it suitable for application in pavement management systems. In the proposed methodology decreases reliance on iterative trial-and-error methods for conducting backcalculation analysis, thus allowing increasing computational efficiency in large-scale pavement evaluation projects. Consequently, the developed methodology may be considered as an advantageous tool in pavement engineering practice.

8. Sensitivity and Reliability Analysis

The importance of sensitivity and reliability analysis cannot be overlooked when it comes to analyzing the efficiency of pavement backcalculation models under different structural configurations. In this current study, sensitivity and reliability analyses were conducted to evaluate the impact of DBPs on the determination of M_L of pavements and to verify the reliability of the proposed seed modulus estimation approach. Moreover, uncertainty analysis was conducted to determine sources of uncertainty in pavement backcalculation analysis.

8.1. Sensitivity Analysis of Deflection Basin Parameters

The sensitivity analysis was conducted to examine the effect of DBPs on the prediction of the pavement layer modulus. From the analysis, it was observed that SCI was highly sensitive to the stiffness of bituminous layer due to its reliance on near-surface deflections.

On the other hand, BDI had a strong relationship with the granular layer, while BCI was mostly affected by the subgrade support conditions. It was concluded from the sensitivity analysis that the chosen DBPs adequately reflected the contribution of pavement layers and were appropriate for seed modulus estimation.

8.2. Reliability Analysis of Proposed Approach

Reliability of the proposed approach based on DBP was tested through regression performance, stability in terms of convergence, and validation through RMSE value. It is observed that the regression models developed generated reliable seed modulus values for flexible pavement sections characterized by good, moderate, and poor levels of distress. The proposed method showed convergence stability and generated relatively low RMSE values from 2.4% to 9.1%, demonstrating high accuracy of pavement deflection prediction. The findings confirm the reliability and application of the proposed technique in flexible pavement structural assessment.

Table 11. Reliability assessment of developed DBP-based framework

S.No.	Assessment Parameter	Observation
1	Regression Stability	High
2	Prediction Consistency	Good
3	Convergence Reliability	Improved
4	RMSE Performance	Acceptable
5	Computational Efficiency	High

8.3. Uncertainty Analysis

An uncertainty analysis was performed to determine the factors affecting the prediction and backcalculation of pavement modulus. The main sources of uncertainties are related to variations in the FWD testing process, temperature effects, material variability, and the assumptions made during the layered elastic analysis. Despite all these uncertainties, the developed model was found to provide adequate accuracy and stability for all selected pavement sections.

Table 12. Sources of uncertainty in pavement backcalculation analysis

S.No.	Source of Uncertainty	Influence on Analysis
1	FWD Measurement Variability	Affects deflection accuracy
2	Temperature Variations	Influences pavement stiffness
3	Material Heterogeneity	Causes modulus variability
4	Layered Elastic Assumptions	Influences simulated response

9. Conclusion

The current research has offered a rational DBP approach to more accurately predict the seed moduli during the back calculation process of three-layer flexible pavement. A large database containing 7000 pavement responses was created through the use of IIT-PAVE software by considering different combinations of pavement h_L and elastic moduli values suitable for Indian flexible pavements. The regression models showed excellent predictive ability, with the coefficients of determination (R^2) being 0.96, 0.95, and 0.81 for bituminous, granular, and subgrade layers, respectively. The findings suggest that SCI, BDI, and BCI are highly sensitive to pavement structural layers and can adequately capture the characteristics of pavement structural behavior. Therefore, the DBP-based method presented herein provides a logical basis for the prediction of realistic seed moduli in pavement backcalculation.

Results obtained from back calculation analysis using the KGPBACK software revealed that the seed modulus approach greatly enhanced stability and consistency of convergence and prediction in different distress states of pavements. Pavements with good structural condition had high layer stiffness but low deflection basins, while pavements with poor structural condition had low modulus but high deflection basins. The results proved the high impact of distress state of pavements on structural behavior and modulus determination. One issue with the developed regression model is that a few of the predicted stiffnesses of the bituminous seed moduli lie marginally beyond the calibration range used in developing the model. These predicted values, although valid in physical terms, can be enhanced through further calibration using data from low-stiffness pavements. The suggested framework achieved superior accuracy in seed modulus prediction, better convergence in backcalculation, and increased reliability under different pavement distress conditions in comparison with currently available prediction techniques, due to the utilization of layer-sensitive DBPs in conjunction with an extensive calibration database.

The validation of the suggested method through RMSE analysis revealed that the suggested method was more accurate than the existing empirical method in terms of prediction. The suggested framework provided RMSE values within the range of 2.4% to 9.1%, while the existing framework provided RMSE values within the range of 4.2% to 10.8%. The low values of RMSE in the suggested method suggest high accuracy in predicting pavement deflections. The sensitivity analysis proved that the selected DBPs accurately represent the structural properties of different pavement layers. Reliability assessment showed that the methodology developed is stable and efficient in terms of modulus estimation for different pavement distresses. The framework is also capable of minimizing the impact of uncertainty related to the choice of the seed modulus. It should be noted that the current study is constrained by considering only three-layer flexible pavements and certain pavement segments for certain distress scenarios. The models formulated in the current paper were formulated based on the assumptions of layered elasticity and may not properly model nonlinear and viscoelastic characteristics of the pavement material under varying environmental and traffic loads. Furthermore, the application of the proposed approach to composite pavements and highly deteriorated pavements needs to be investigated. Future studies could concentrate on combining machine learning/deep learning methods with DBP-based modeling techniques, including temperature correction models, among other issues.

References

[1] Soughah Al-Samahi et al., “A Comparative Study of Pavement Roughness Prediction Models under Different Climatic Conditions,” *Infrastructures*, vol. 9, no. 10, pp. 1-25, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Omar Elbagalati et al., “Development of the Pavement Structural Health Index Based on Falling Weight Deflectometer Testing,” *International Journal of Pavement Engineering*, vol. 19, no. 1, pp. 1-8, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[3] Hao Wang et al., “Prediction of Airfield Pavement Responses from Surface Deflections: Comparison between the Traditional Backcalculation Approach and the ANN Model,” *Road Materials and Pavement Design*, vol. 22, no. 9, pp. 1930-1945, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] Marcos Rocha et al., “Influence of Seed Layer Moduli on Backcalculation Procedure and on Overlay Design of Flexible Pavements,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2676, no. 5, pp. 341-357, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[5] Arman Hamidi, Inge Hoff, and Helge Mork, “A Sensitivity Analysis on the Simulated Measurements of Traffic Speed Deflection Devices,” *International Journal of Pavement Engineering*, vol. 25, no. 1, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Guozhi Fu et al., “A Viscoelastic Wave Propagation Approach for Dynamic Backcalculation of Layer Properties of Asphalt Pavements under an Impact Load,” *Computers and Geotechnics*, vol. 176, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[7] Paweł Tutka et al., “Sensitivity Analysis of Determining the Material Parameters of an Asphalt Pavement to Measurement Errors in Backcalculations,” *Materials*, vol. 14, no. 4, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Mateusz Kałuża, and Mirosław Kotasiński, “Relationship between Deflection Basin Parameters and Backcalculated Pavement Layer Moduli,” *Archives of Civil Engineering*, vol. 70, no. 2, pp. 149-162, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[9] Mofreh Saleh, "Simplified Approach for Structural Capacity Evaluation of Flexible Pavements at the Network Level," *International Journal of Pavement Engineering*, vol. 17, no. 5, pp. 440-448, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[10] José Geraldo de Souza Júnior, "*Application of the New Method for Dimensioning Asphalt Pavements to Sections of a Federal Highway*," Master's Thesis, University of Rio de Janeiro, pp. 1-236, 2018. [Google Scholar] [Publisher Link]

[11] Marcos Rocha, Geraldo Marques, and Rafael Silva, "Predicting Equations for Determining Layer Elastic Moduli by using Deflection Basin Parameters (DBPs) from Falling Weight Deflectometer," *International Journal of Pavement Engineering*, vol. 23, no. 13, pp. 4708-4720, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] Marcos Lamha Rocha, "*Influence of Initial Resilience Moduli on the Back-Analysis Procedure of Flexible Pavements*," Master's Thesis, Federal University of Juiz De Fora, pp. 1-247, 2020. [Google Scholar] [Publisher Link]

[13] Vidhi Vyas, Ajit Pratap Singh, and Anshuman Srivastava, "Prediction of Asphalt Pavement Condition using FWD Deflection Basin Parameters and Artificial Neural Networks," *Road Materials and Pavement Design*, vol. 22, no. 12, pp. 2748-2766, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] Luis Fuentes et al., "A Probabilistic Approach to Detect Structural Problems in Flexible Pavement Sections at Network Level Assessment," *International Journal of Pavement Engineering*, vol. 23, no. 6, pp. 1867-1880, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] R. Diaz Flores, "*Falling Weight Deflectometer Tests on Multi-Layered Pavement Structures: Innovative Experiments and Multi-Method Structural Simulations*," PhD Thesis, Vienna University of Technology, pp. 1-157, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[16] Xueqin Chen et al., "Evaluation and Prediction of Pavement Deflection Parameters Based on Machine Learning Methods," *Buildings*, vol. 12, no. 11, pp. 1-15, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] Arman Hamidi, Inge Hoff, and Helge Mork, "Elastic and Viscoelastic Back-Calculation of Pavement Layers' Moduli using Data Obtained from Traffic Speed Deflection Devices," *Construction and Building Materials*, vol. 447, pp 1-22, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[18] Alireza Jafari Anarkooli, Iliya Nemtsov, and Bhagwant Persaud, "Safety Effects of Maintenance Treatments to Improve Pavement Condition on Two-Lane Rural Roads—Insights for Pavement Management," *Canadian Journal of Civil Engineering*, vol. 48, no. 10, pp. 1-22, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[19] Hossam S. Abd El-Raof et al., "Simplified Closed-Form Procedure for Network-Level Determination of Pavement Layer Moduli from Falling Weight Deflectometer Data," *Journal of Transportation Engineering, Part B: Pavements*, vol. 144, no. 4, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[20] "*IRC:82: 2015 Code of Practice for Maintenance of Bituminous Road Surfaces of Highways*," The Indian Roads Congress, 2015. [Google Scholar]

[21] Hao Wang et al., "Structural Assessment of Asphalt Pavement Condition using Backcalculated Modulus and Field Data," *Construction and Building Materials*, vol. 211, pp. 943-951, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[22] Xinyu Guo, Yue Chen, and Nan Sun, "Robust Pavement Modulus Prediction Using Time-Structured Deep Models and Perturbation-Based Evaluation on FWD Data," *Sensors*, vol. 25, no. 17, pp. 1-28, 2025. [CrossRef] [Google Scholar] [Publisher Link]