Designing a Mathematical Model for Predicting the Mechanical Characteristics of Asphalt Pavements Using Dynamic Loading

Hamid Behbahani[1] **and Seyed Ali Sahaf**[2]
[1]Professor, Faculty of Civil Engineering, IUST, IRAN
[2]PhD Candidates, Faculty of Civil Engineering, IUST, IRAN, Email:ASSAHAF@YAHOO.COM

Abstract: *The available methods for predicting mechanical characteristics of pavement layers are categorized into two general groups, Destructive and Non-destructive. In destructive method, using coring and pavement subgrade and performing necessary experiments on them, the quantities of layers properties will be identified. In Non-destructive method, the attained deflection is measured by applying the loading on pavement surface using equipments such as FWD which charges the impact dynamic load, and the mechanical characteristics of pavement layers are determined using back calculations. The procedure of conducting these calculations is that by knowing the thickness of the pavement layers and assuming the initial amounts for mechanical characteristics of the layer, the attained deflection at the desired points on the pavement surface will be calculated. Then, new figures are assumed for the characteristics of layers in a reattempt and calculations are repeated again. This trial and error is continued until the produced basin deformations from the calculations with true value, differs in an acceptable range. Using this method may have no accurate and single answer, since the various compositions of layers characteristics can produce similar deformations in different points of pavement surface. In this article, using an innovative method, a measurement is taken in constructing and introducing a mathematical model for determining the elastic module of surface layer using deflections attained from FWD loading equipment. The procedure is such that by using dynamic analysis software of finite elements like ABAQUS and ANSYS, the deformation of corresponding points on the surface of the pavement will be attained by FWD loading equipment. This analysis will be performed on a number of pavements with different thicknesses and different layers properties. The susceptibility analysis of different points deformations show, which will be performed as a result of the change of properties and layers thicknesses. Using this artificial data base as well as deflection basin parameters (DBP), a measurement will be taken toward constructing a regression model for determination of asphalt layer model, i.e.* $E_{ac}=f(DBP)$ *function shall be attained. To achieve the maximum correlation coefficient, an attempt is made to use the parameters of deformations basin which has the most susceptibility in changing asphalt layer module.*

Keywords: *Asphalt pavements, FWD, Prediction models, FEM analysis.*

1. Introduction

Using non-destructive deflection tests is an important part of structural evaluation of the pavements. In this way, various equipments in the world are used, such as Falling Weight Deflectometer (FWD), Dynaflect, etc [1].

Among all NDT methods FWD is the most widely used technique because of its ability to successfully simulate traffic loadings and capacity to produce larger amount of deflection data in unit time [2].

The FWD is an excellent device for evaluating the structural capacity of pavements in service for rehabilitation designs.

Generally, surface deflections obtained from FWD testing have been used to back-calculate in situ material properties using an appropriate analysis technique to predict the pavement responses and layer condition.

In traditional methods, deflections obtained from FWD test are commonly utilized for the back-calculation of mechanical pavement properties using specific software tools [3].

The goal of this research is to develop a reliable process which can estimate pavement layers conditions by using deflections attained from FWD. In the conventional method of analyzing FWD results, back-calculations are used to solve the problem, in such a manner that by using the maximum produced deformations measurements of road surface (due to impulse loading of the above equipment) under load points and in the various radial intervals, as well as measuring different thicknesses of pavement layers, an attempt is made to calculate the layers modules in such a way that calculative forms from mechanical formulas, have the least level of errors with the measured deformations by geophones [4]. In other words, the following target should be minimized:

$$\text{Min } \varepsilon^2 = \sum_{i=1}^{S} \left(\frac{W_i^m - W_i^c}{W_i^m} \right)^2 \qquad (1)$$

Where: ε = comparative error between measured deformation and calculative deformation
S = Number of geophones
W_i^m = Measured deformation of I_m sensor
W_i^c = Calculative deformations of I_m sensor

Of course, it can be weighed the measured error in each sensor and adjust the target function by means of it. Because of accuracy has more importance in predicting the deformations of some points. For example, in intervals far from the load, which are measured by last geophones, the deformations are very small and the subgrade module is estimated by considering them. Any error occurring in these estimations may influence on other calculations. Different softwares are used for back-calculations, such as ELMOD, MODULUS, WESDEF, etc. several experiences have shown that using these plans in the same situations have had different responses because different compositions of mechanical properties of the layers can produce relatively same deformations in pavement surface [5]. Finally, it can be said that the above method is not fast and also the target function may have several local minimums and the obtained results based on this method fall into error, which in this case entering the initial values suitable to this plan, is very important. In Iran, the ELMOD software is used for analyzing FWD outputs and no investigations has been made on it. Therefore, it is necessary to seek other analyzing methods for solving this problem. This research is being conducted following the construction of a regression model for predicting the properties of pavement layers using the produced deformations by FWD.

The existing methods for analyzing structural evaluation of pavements are generally as follows:

One approach is to conduct deflection test on a number of pavement with varying depth of different layers, and varying distress characteristics in different environmental conditions and to relate the observed deflection behavior to the input variables, so this approach called an empirical approach. This approach need a large number of combinations of these factors and it will be time consuming and costly and to some extent impossible due to the large of data requirements.

The other approach, so-called a mechanistic approach, is to employ mechanics of materials equations that relate an input FWD loading history to an output or pavement responses such as deflections.

The research approach taken in this study describes a mechanistic-empirical condition assessment of pavement layers. This approach optimizes the application of the two approaches described above this paragraph.

ANSYS finite element program was used in this research to develop synthetic databases that cover all the pavement structures constructed as usual [6].

Finite element analysis was performed on various pavement structures modeled by both linear and nonlinear elastic material models. Pavement response models and pavement performance models were used in developing for regression modeling.

A 64-KN FWD load was used in the finite element modeling to compute deflections, stress and strain at various locations in the pavement system that are critical for the condition and performance evaluation. The resulting synthetic data bases are composed of pavement structural and material characteristics (such as layer thicknesses and material coefficients) as well as pavement responses (such as strains, stresses and deflection).

Both linear and nonlinear models for flexible pavements were produced.

Synthetic data were generated for the full range of pavement properties found in Iran's highway.

These synthetic databases were studied systematically using regression analysis.

Standard statistical software available within SPSS and MATLAB were utilized to carry out the regression.

2. Back-Calculation

In pavement engineering literature this idiom means the realizations of material properties in road layers using the produced deformations resulted from loading. The process of back calculations has been considered very much sensitive to the kind of analysis and theories [7]. Also, the back-calculation process of the elasticity modulus of layers is susceptible to entered variations like the thickness of layers and the depth of bedrock. Most of the methods of back-calculation use the minimizing error technique to conform to the calculative and measured deflection basins. Because of these problems, researches sometimes seek alternative methods such as statistical regression equations method. Such methods are much faster and they don't need any trial and error process. In this field, the researchers have provided many suggestions. The suggested equation for determining the elasticity modulus of asphalt concrete layer by maximum deflection is as follows [8]:

$$\text{Log}\,(E_{ac}) = A + B\,(D_0) + C\,(D_0)^2 \quad (2)$$

Where:
E_{ac}= modulus of asphalt concrete layer
A, B, and C = constant
D_0= maximum deflection under load

Using the susceptibility analysis results and sensors arrangement in two longitudinal and transversal directions, Romero and Roque achieved the following relations in determining the elasticity modulus of asphalt layer [9]:

$$E_{ac}=[78.2254(H_{ac})^{0.5554}]*\{[D_0-D_{25}]^{-0.7966}\} *[D_0-D_{x20}]^{17.47} \quad (3)$$

Where:
E_{ac}= modulus of asphalt concrete layer

Table 1 Material properties and thickness ranges used for linear analysis.

Pavement layer	Thickness(m)	Modulus (pa)	Poisson Ratio
Asphalt concrete	0.075, 0.15, 0.25, 0.40	1E9, 2E9, 4E9, 1E10	0.35
Aggregate Base	0.15, 0.30, 0.75	1E8, 3E8, 7.5E8, 1.5E9	0.35
Sub-grade *	0.5, 1.5, ∞	2.5E7, 7.5E7, 1.5E8	0.40

* While the sub grade depth has been given a finite number, the bedrock under it has been considered to have a zero deformation

Table 2 Material properties and thickness ranges used in nonlinear ANSYS runs.

Pavement Layer	Thickness (m)	Modulus (pa)	Poisson Ratio
Asphalt Concrete	0.075, 0.15, 0.25, 0.40	1E9, 2E9, 4E9, 1E10	0.35
Aggregate Base	0.15, 0.30, 0.75	Thompson model**	0.35
Sub-grade	0.5, 1.5, ∞	Bi-linear model***	0.40

$$**E_{base}=K_1\theta^{K2} \tag{4}$$

$$***E_{sg} = \begin{cases} K_1 + K_3 (K_2 - \sigma_d) \\ K_1 - K_4 (\sigma_d - K_2) \end{cases} \tag{5}$$

Where: K_1, K_2, K_3, and K_4 = constant, σ_d= deviator stress

D_0= maximum deflection under load
D_{25}= deformation in radius interval of 25 cm from load
D_{x20}= Deflection at 20 cm longitudinal directions and x cm transversal directions
H_{ac}= thickness of asphalt concrete

3. Synthetic Databases

Synthetic deflections were calculated using ANSYS finite element commercial software package for various pavement structures.

In flexible pavement where nonlinearity was included in unbound layers, additional material properties had to be included.

In this approach, a range of thicknesses and moduli was defined for each pavement layer. FEM models were then created with values randomly selected from the given thicknesses and modulus range [6].

Performing the analysis conducted with ANSYS, the thickness and layers modulus were supposed to be variable and the rest of the required data were supposed to be constant in the program.

Table 1 summarizes the thickness range and actual modulus and thickness values used for each pavement type in linear condition, and Table 2 illustrates the modulus and thickness range used in creating the additional nonlinear synthetic database [5]. This effort resulted in a total of 1728 cases for the linear database and 144 cases for nonlinear database that must be an analyzed.

All the above modes were loaded with 64KN FWD force with a 15cm radius and the attained stress will be about 900 Kpa.

Figure 1 shows the relative meshing in the ANSYS software.

Then the attained deformation was achieved at the loading center and in radius intervals of

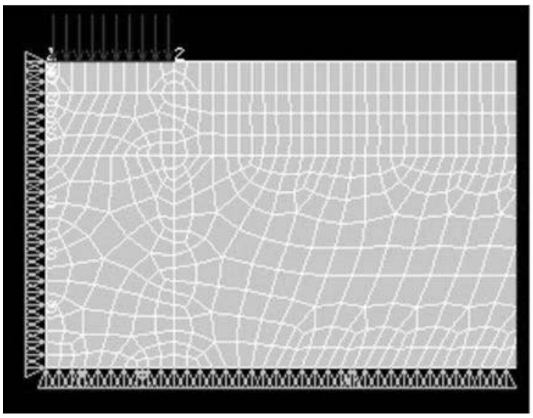

Fig.1 Schematic meshing in ANSYS software

Table 3 Deflection Basin Parameters (DBP)

Deflection Parameter	Formula
Area	$\text{Area} = \dfrac{6\,(D_0 + 2D_{30} + 2D_{60} + D_{90})}{D_0}$
Base Curvature Index	$BCI = D_{60} - D_{90}$
Base Damage Index	$BDI = D_{30} - D_{60}$
Surface Curvature Index	$SCI = D_0 - D_{30}$
Shape Factors	$F_1 = \dfrac{D_0 - D_{60}}{D_{30}}$, $F_2 = \dfrac{D_{30} - D_{90}}{D_{60}}$, $F_3 = \dfrac{D_{60} - D_{120}}{D_{90}}$

30cm from it up to 180 cm, which were named D_0, D_{30}, D_{60}, D_{90}, D_{120}, D_{150}, and D_{180}, respectively which produce a deformation basin.

Also the mentioned values were calculated in the critical points in which the cracking and stripping failures are occurred due to increased stress and tension, such as the stress and tension at the bottom of the asphalt layer across the loading center, and the other on the top the sub grade layer across the loading center.

Deflection Basin Parameters (DBP), which are derived from FWD deflection measurements, are established to be good indicator of selected pavement properties and conditions. They are useful for making regression model.

The advantage use of deflection basin parameters, instead of the deflection measurement alone, was used by other researcher [10].

Various DBPs were studied as condition indicator for different layers. All the DBPs utilized in this research summarized in Table 3.

4. Parametric Sensitivity Study

In the FEM analysis with ANSYS, thickness and modulus for each layer were changed for making synthetic database. It was studied to determine the most effective DBPs in describing the condition of each layer of pavement. For this reason, pavement characteristics in question were fixed to minimum and maximum Values. All other conditions were allowed to change, and DBPS were evaluated. The results were analyzed and a Percent Root Mean Square Error (%RMSE) was evaluated for DBP and

Table 4 Parametric sensitivity study results for layer of pavement

DBP	RMSE for H_{ac} (%)	DBP	RMSE for H_{abc}	DBP	RMSE for H_{sg}	DBP	RMSE for E_{ac}	DBP	RMSE for E_{abc}	DBP	RMSE for E_{sg}
BDI	286	BCI	172	F_3	256	SCI	812	BDI	243	BCI	106
SCI	247	BDI	144	F_2	128	F_1	278	BCI	191	F_1	54
BCI	176	F_3	103			BDI	243	SCI	109		

the seven measured deflections.

Therefore, the DBPs or deflection with the largest RMSE were considered the best indicator for that particular pavement characteristic. For example, if the inner sensor measurements define a DBP, then that DBP better characterizes the condition of the asphalt layers, because of the shape of stress distribution. Table 4 shows the results of the parametric study for these pavements.

The DBPs chosen from the sensitivity study were investigated for Layer condition indicator.

Then a set of regression equations correlating the DBPS to layer condition indicators was developed form the synthetic data. The final results of these researches are presented below.

5. Regression Equations for Prediction Pavement Layer Condition

5.1. Asphalt Concrete Layer Strength

At first, the regression based approaches were developed to predict Eac. These approaches were developed using the synthetic database from linear and nonlinear finite element analysis. The following relationship best fits the synthetic data to predict Eac.

$$\mathrm{Log}(E_{ac}) = -4.13\mathrm{Log}(BCI) - 11.28\mathrm{Log}(SCI) + 14.63\mathrm{Log}(BDI) - 0.81\mathrm{Log}(H_{ac}) + 2.99,\ R^2 = \%68.3$$

For Linear Analysis (6)

$$\mathrm{Log}(E_{ac}) = -10.19\mathrm{Log}(SCI) + 5.87\mathrm{Log}(BDI) - 0.898\mathrm{Log}(H_{ac}) + 1.33,\ R^2 = \%79.6$$

For Non-Linear Analysis (7)

Where:

E_{ac}= modulus of asphalt concrete layer,

BCI, SCI, and BDI=define at table 3,

H_{ac}=thickness of asphalt concrete layer

There has been an attempt to use those parameters of deformation basin, which have the most susceptibility to asphalt layer module. The above equations with high correlation coefficients are suitable for predicting the asphalt layer module using the obtained deformations form FWD equipment. Moreover, since the FWD data was available in some sections of the road and the laboratory coring for determining asphalt elasticity module using UTM equipment was possible, an attempt was made to investigate the obtained models on the basis of field database method for asphalt layer.

Therefore, the data from one section of the Birjand – Ghaeen road were used to verify this procedure.

For this purpose, the data from field was screened, because some distresses cause discontinuities in pavements and show unusual shapes. The following criteria were used to identify such unusual cases:

Criterion 1: $D_i < D_{i+1}$, i = 1, 2…6

Criterion 2: $E_i > E_{i+1}$ and $E_i > E_{i-1}$, i = 2, 3…6

Table 5 Predicted Resilient Modulus (MPa) from Different Approaches

No. Sample	Test Method	Linear Regression	Non-Linear Regression	Back_Calculate with ELMOD	Testing with UTM
1		2475	2153	2308	1808
2		2407	2264	2601	1865
3		1874	1656	1745	1836
4		1653	1547	1458	1687

Where D_i is the deflection at the i^{th} sensor, and E_i is the surface modulus at the i^{th} sensor. Criterion 1 is used to check if an outer sensor deflection is greater than inner sensor deflection, which happens when sever discontinuities exist in upper layers.

Criterion 2 is used to avoid the appearance of peak surface modulus value between the center and the outer sensor. Because in intact pavement, peak surface modulus occurs at either the center sensor due to the high stiffness of the Asphalt layer, or the outer sensor (7^{th} sensor) due to the high stiffness of the stiff layer.

These indications were confirmed by visual observation of the cores obtained from the test locations, and then the best data was chosen to verify the regression models.

The asphalt modulus for each FWD test was predicted using the regression based from: equation 1, and also by using back calculation method with ELMOD program, and at last asphalt modulus was obtained from core sample in laboratory. Universal Test Machine (UTM-5) was used to predict the resilient modulus of asphalt.

Table 5 Compares these predictions and show that the values obtained from regressions in this study, are suitable in predicting the asphalt module.

Comparison of laboratory resilient modulus with back-calculated elastic moduli by ELMOD program that used FWD tests in the field and predicted moduli from regression method, verified the application regression method that obtained from nonlinear synthetic database.

Taking into account that a large number of different states of thickness and the properties of different pavement layers have been considered in constructing these models, so, the total environment conditions and the type and gradation of asphalt which influence on its mechanical properties, have been included indirectly in constructing these models.

5.2. Cracking Potential

For asphalt concrete pavements, the tensile strain at the bottom of asphalt layer is good indicator for pavement cracking potential. Because of the nonlinear synthetic database has better behavior description than linear database, by now the other regression models making by nonlinear database.

On the other hand, consideration of non-linearity in unbound layers is necessary for accurate modeling of a flexible pavement structure.

The tensile strain at the bottom of asphalt layer is predicted from the following equations that were developed from the nonlinear synthetic database.

Table 6 Comparison of ε_{ac} valued that obtain from FWD with monitoring.

No. of sample	1	2	3	4	5
ε_{ac} values from FWD (μ strain)	88	127	114	185	149
ε_{ac} values from field (μ strain)	64	118	134	142	133

$$Log(\varepsilon_{ac}) = -2.69Log(BCI) - 5.54Log(SCI) + 8.84Log(BDI) + 0.64Log(H_{ac}) + 1.13,\ R^2 = \%65.1 \quad (8)$$

Where:
ε_{ac} = tensile strain at the bottom of asphalt layer,
BCI, SCI, and BDI= define at table 3,
H_{ac}= thickness of asphalt concrete layer

Then the fatigue life of asphalt pavement can be determined using the calculated strains resulted from loading with FWD equipment, by using the fatigue life models.

This equation was developed from the synthetic database of nonlinear analysis with various combinations of pavement structures and material properties. This formula can be verified by monitoring of pavement layer and using strain gage at the bottom of asphalt layer, and information need to receive from field data.

Very little high quality data were present in Iran, and then some available site data were used in the validation of this procedure. Data Pave 2.0 data were used to verify this method [11].
Data Pave 2.0 is an extensive database of pavement testing information in USA, and for this reason, information obtained from Data Pave was considered and utilized for procedure verification.

The data from Nebraska aggregate base pavement test section in Data Pave 2.0 were used to validate the above equation. The ε_{ac} values were first calculated from FWD test and above equation, and also obtained from measurements recorded in field. The ε_{ac} values from FWD recorded against the ε_{ac} values from field measurements, and show that using from this equation is suitable for prediction cracking potential of asphalt layer.

5.3. Base Strength

Prediction of base layer condition was a complex problem in this research. Based on the analysis of synthetic data, only a small portion of pavement surface deflections from FWD testing is affected by the base layer properties, and the result show that the quality of base layer has no significant effect on pavement surface deflections.

Therefore, it could not to make a good regression model with a high correlation coefficient.

5.4. Subgrade Strength

Similar to base layer pavement, also for subgrade layer a good regression model was not found with DBP produce from FWD, however the strain on the top of subgrade layer represents subgrade strength or rutting potential. Therefore, a regression model was tried to make with this parameter.

Based on the sensitivity study, BCI appeared to be sensitive to subgrade stiffness, and the BDI is in this manner.

The following relationships were developed to estimate ε_{sg} value in microstrain.

$$Log(\varepsilon_{sg}) = -0.53\ Log(BCI) - 0.85\ Log(SCI) + 1.74\ Log(BDI) - 0.06\ Log(H_{ac}) - 0.15\ Log(H_{abc}) + 3.3,\ R^2 = \%81.5 \quad (9)$$

Where:
ε_{sg} = compressive strain on the top of

Table 7 Comparison of ε_{sg} valued that obtain from FWD with monitoring.

No. of sample	1	2	3	4	5
ε_{sg} values from FWD(μ strain)	32	26	16	41	37
ε_{sg} values from field (μ strain)	49	31	38	35	40

subgrade layer,
BCI, SCI, and BDI=define at table 3,
H_{ac}=thickness of asphalt concrete layer
H_{abc}= thickness of base layer

Then the life of asphalt pavement on the basis of rutting depth can be determined using the calculated strains resulted from loading with FWD equipment, by using the rut depth models.

This formula can be verified by monitoring of pavement layer and using strain gage on the top of subgrade layer, like the above method for the tensile strain at the bottom of asphalt layer.

The ε_{sg} values were first calculated from FWD test and above equation, and also obtained from measurements recorded in field. The ε_{sg} values from FWD recorded against the ε_{sg} values from field measurements, and show that using from this equation is suitable for prediction rutting potential of pavement.

6. Interpretation and Application

The predicted method presented here was to determine the overall procedures for pavement layer condition assessment using condition indicators predicted from FWD measurements. As presented in previous section, E_{ac} and ε_{sg} seem to be good condition indicators for asphalt layer, while ε_{sg} and BCI were found to effectively represent subgrade layer conditions.

These condition indicators can be categorized into these groups: layer moduli, critical stresses and strains, and DBPs.
Other application from this finding is the method for determining the residual life to pavement can be cracked or has rut depth.

7. Conclusions and Suggestions

All of the effort made in this research is to develop the applicable procedures for evaluating pavement layer conditions from the FWD raw data.

Condition assessment of pavement layers using deflection data has been investigated.

- At first, it begin by constructing and analysis of synthetic data generated from a FEM structural model, reasonably estimates actual field conditions for the ranges of pavements under consideration.

- The nonlinearity of unbound aggregate base and subgrade is important to estimate responses of aggregate base pavement.

- For this pavement, E_{ac} and ε_{sg} can be used as an indicator to detect cracking in asphalt layer. esg, BCI appeared to be good condition indicators for subgrade. For intact pavements, the pavement overall fatigue cracking and rutting potentials are mainly controlled by ε_{ac} and ε_{sg}.

- For this pavement, the analysis from synthetic data showed that SCI has high correlation to predict asphalt modulus, and field data verified it. Also, high correlation was found between BDI and ε_{ac}, and suggested to approve it with pavement monitoring in the field in the next researches.

- The pavement layer condition assessment procedures developed from this research are different from traditional deflection analysis programs in that some of the relationships constituting these procedures do not require all seven deflections, but require only a portion of deflection basin. This feature allows the analysis of irregular deflection basins that are observed in distressed pavements for layer condition assessment.

- High quality field and lab data is need to improve the effectiveness of prediction models especially base and subgrade layer.

8. References

[1] Shahin , M.Y. , Pavement Management for Airports, Roads and Parking Lots, Great Britain, Champion & Hall Publishing , 1992.

[2] Hoffman, M.S. and Thompson, M.R. , Backcalculating Nonlinear Resilient Moduli from Deflection Data, Transportation Research Record 852, TRB, National Research Council, Washington D.C, 1982, pp. 42-49.

[3] Ulidtz, P, Nonlinear Backcalculation Help, NDT of Pavements and Backcalculation of Moduli, STP 1375, ASTM pub., PA. 2000.

[4] Noureldin, A. and Harris, D., Network Pavement Evaluation with FWD and GPR, Transportation Research Record 1860, TRB, National Research Council, Washington D.C, 2002, pp. 90-98.

[5] Huang, Y.H., Pavement Analysis and Design, Prentice Hall, 1993.

[6] Dr. Jahed, Manual of ANSYS, Amirkabir pub., 1382.

[7] Sebaaly P.E., Phase Lag Effects on Analysis of FWD Data, Nondestructive Testing of Pavements and Back Calculation of Moduli, Second Volume, Philadelphia, USA, 1994.

[8] Crovetti J.A., The Effect of Annular Load Distributions on the Back Calculation of Moduli of Asphalt Pavement Layers, Nondestructive Testing of Pavements and Back Calculation of Moduli, Second Volume, Philadelphia, USA, 1994.

[9] Roque , R. and Romero, P. and Shen, X. and Ruth , B. E. , Prediction of Asphalt Pavement Structural Layer Moduli Using Optimization FWD Configuration, Association of Asphalt Paving Technology, AAPT, Vol. 64, PP 278 – 305, 1996.

[10] Andrew, M.Johnson, Baus, R.L., Simplified Direct Calculation of Subgrade Modulus from Nondestructive Pavement Deflection Testing, Transportation Research Record 1406, TRB, National Research Council, Washington D.C, 1991.

[11] The Long-Term Pavement Performance (LTPP) Program Data Pave user guide, online on website.