Analysis of Procedures for Establishing In Situ Subgrade Moduli

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Through the efforts of the Strategic Highway Research Program Long-Term Pavement Performance study, a vast amount of data has been collected on hundreds of pavement test sections across North America. As part of this effort, extensive subgrade data have been collected, including Atterberg limits, gradations, moisture contents, deflection data, laboratory resilient moduli, and subgrade profiles. With this wealth of information on the subgrade and its associated properties, it becomes possible to evaluate previously proposed methods for determining the subgrade resilient moduli and possibly to develop new models to improve the ability to estimate soil support conditions for pavement design purposes. Three methods for determining the subgrade resilient moduli are considered: laboratory testing, backcalculation using deflections measured from nondestructive testing (NDT), and an estimation equation contained in the 1986 *AASHTO Guide.* There is currently no consensus as to which moduli value should be used for pavement design. An attempt is made to develop relationships between the various sources for moduli prediction. Based on the data currently available, there appears to be little if any relationship between these various methods for determining the resilient modulus of a subgrade. Efforts were made to develop moduli prediction equations based on various subgrade properties and NDT. The subgrades were separated into basic soil classifications (clay, sand, and silt) and models were developed for each subgrade type. Each model contains the load and sensor 7 reading from falling weight deflectometer test results. Other properties that proved to be significant were the thicknesses of the pavement layers, percent saturation of the subgrade, dry densities, and specific gravities.

A pavement structure is designed to distribute the vehicle loadings to which it is exposed. If that pavement structure is not designed appropriately for its underlying support, it will fail. Pavement designers must take into account the properties of the subgrade on which the road is built to ensure that sufficient pavement structure is provided to adequately distribute the anticipated loading.

Taking these fundamentals of pavement design into account, the stiffness of the subgrade is obviously an important parameter in pavement design. Many unique methods have been developed over the years for representing the subgrade support and estimating the subgrade stiffness, but to date there is no consensus on how to best establish the stiffness of the subgrade for pavement design purposes.

Through the efforts of the Strategic Highway Research Program (SHRP) Long-Term Pavement Performance (LTPP) Program, considerable data have been collected on pavement subgrades. In addition to the fundamental subgrade properties (e.g., Atterberg limits, gradation, and in situ moisture content), deflection data, lab resilient moduli, and data on the subgrade profile to a depth of 20 ft have also been accumulated. With this wealth of information on the subgrade and its associated properties, relationships that exist among all of these various properties should be established to provide a more comprehensive understanding of subgrade support for future pavement design work. Several researchers have reported on various facets of this complicated subject (*1,2*). The LTPP data base, however, provides such a vast array of data types for so many sections (more than 700) that some of the methods previously prescribed for estimating soil support conditions can now be evaluated and modifications established that will ultimately enhance predictive capabilities. Data from only the North Atlantic and Southern SHRP regions were available for this analysis.

As part of the LTPP Program, backcalculation of test section deflection data has been conducted using the MODULUS program to establish the layer moduli for each test section. Subgrade moduli from these backcalculation procedures were evaluated in conjunction with the lab-determined moduli and estimated subgrade moduli on the basis of procedures prescribed in the 1986 *AASHTO Guide to the Design of Pavement Structures* (*3*). Comparisons of these three sources of subgrade moduli were used along with the other subgrade properties in an attempt to identify where relationships exist among these various sources of subgrade moduli data and to identify methods for estimating subgrade stiffness in the absence of resilient modulus or deflection testing. Although there has been some debate as to which source of subgrade stiffness data is best suited for pavement design, no efforts are made here to prove or disprove the merits of either source.

SHRP-LTPP DATA BASE

Under SHRP, many different types of data have been collected on various test sections within the United States and Canada, including information about traffic, pavement materials, and structural parameters, as well as monitoring information. All of these data are stored in a data base in the form of tables using the Oracle program. Under SHRP, the United States and Canada were divided into four regions, with each region responsible for all of the data collection and monitoring within its respective area. Each region also controls the data base for that region and semiannually uploads its data to a national data base in Washington, D.C. The data used in this analysis were obtained from that data base, and the statistics for the data set are presented in Table 1. Because of testing limitations at SHRP, however, only lab resilient moduli values for the Southern and North Atlantic regions were available for this analysis.

MODULI PREDICTION PROCEDURES

For this analysis, subgrade resilient moduli from three sources were used. The first source was laboratory resilient modulus testing.

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TABLE 1 Statistical Values of Data Set Used in Analysis

Variable	Units	No. of Values	Mean Value	Standard Deviation	Low Value	High Value	Range
Back calculated Modulus	psi	534	29214	29778	0	292000	292000
Laboratory Resilient Modulus	psi	671	9694	3882	0	54023	54023
AASHTO Estimated Resilient Modulus	psi	546	40132	25759	0	260596	260596
In Situ Moisture	%	671	14.8	7.7	1.2	43.4	42.2
Plasticity Index		671	7.8	10	0	61	61
Liquid Limit		671	20.1	18.8	0	81	81
Plastic Limit		671	12.2	11	0	51	51
% passing #200 Sieve	%	671	43.7	28.1	0	99	99
Effective Depth to Rigid Layer	in	523	316	235	43.8	600	556.2
Specific Gravity		671	2.68	0.07	2.49	3.1	0.6
Wet Density		671	123.3	9.0	92.8	150.8	58.0
Saturation		671	67.7	19.7	6.0	162.1	156.1
Dry Density		671	108	10.5	76.6	135.8	59.2
Sensor 7 Deflection	mils	284	1.33	0.64	0.08	4.03	3.45
FWD Load	lbs	284	9335	441	7528	10475	2947
Base Thickness	In	664	8.5	8.91	0	47.1	47.1
Surface Thickness	In	664	11.5	6.01	1.1	34	32.9

"Undisturbed" samples were collected in Shelby tubes where possible. Where undisturbed samples could not be obtained, bulk samples were obtained and samples remolded for testing. The second source was a backcalculation process using measured deflections from all seven sensors of a falling weight deflectometer (FWD). The third source was an estimation procedure using the load and the measured deflection from the seventh sensor of an FWD. The following is a brief explanation of these three sources of subgrade moduli.

Laboratory Estimation of Subgrade Moduli

Laboratory moduli included in this analysis were determined using SHRP protocol P46, "Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils." The modulus from this test is determined from the results of repeated-load triaxial compression tests. The resilient modulus is expressed as the ratio of the amplitude of the repeated axial deviator stress to the amplitude of the resultant recoverable strain, and each value is related to a specific stress state.

The test method consists of applying a repeated axial deviator stress of fixed magnitude, load duration, and cycle duration to a cylindrical test specimen. The specimen is subjected to a constant (static) lateral stress by means of the triaxial test chamber where the specimen is placed for testing. The recoverable axial deformation of the specimen is measured and used to calculate the resilient modulus. For this analysis the resilient modulus values were determined using a deviator stress of 2 psi and a confining pressure of 2 psi (M_{R22}). It was believed that these values best represented the average stress and pressure values that occur in the subgrade under traffic loading and surcharge.

Backcalculated Estimation of Subgrade Moduli

Backcalculation of the subgrade moduli was conducted using a microcomputer-based procedure called MODULUS 4.0 (*4*), which was selected by SHRP for LTPP after careful study of available backcalculation software. This procedure estimates the layer moduli using deflections for seven sensors measured by an FWD. The objective of any backcalculation routine is to process the deflection data and estimate the pavement material properties on the basis of these data and the applied load. This can be accomplished by employing a procedure that predicts a set of parameters that corresponds to the best fit of the measured deflection bowl. Best fit is achieved when the percent error between the measured deflection bowl and the calculated deflection bowl is minimized. A data base of calculated deflection bowls can be generated by elastic layer theory (assuming ranges of material properties) and then used as a comparative tool by which the error is minimized.

Once the error between measured and calculated deflection bowls is minimized, the calculated modulus for each layer of the pavement structure associated with the calculated deflection bowl that best fits the measured bowl together are used as the layer moduli of the existing pavement. In summary, the steps followed by MODULUS to backcalculate pavement layer moduli are as follows:

1. Input measured deflection data obtained from FWD testing, the applied load, and other pavement properties (layer thickness, estimated range of layer moduli, and Poisson's ratio).
2. Generate calculated deflection bowls using elastic layer theory.
3. Minimize the percent error between calculated and measured deflection bowls.
4. Determine layer and subgrade moduli on the basis of calculated deflection bowl that corresponds to lowest percent error.

It should be noted that the MODULUS program is only one of many backcalculation programs available. These programs are developed on basically the same theory, but they can and will generate different results when supplied with the same input. This point is made because the analysis process could also include the results from these other programs, but no effort is made here to do this.

Estimation of Subgrade Moduli from Deflection Testing

The 1986 *AASHTO Guide to the Design of Pavement Structures* (*3*) includes a procedure that uses deflection testing results to estimate the subgrade resilient modulus. Figures 1 and 2 show a typical deflection profile and corresponding stress "bulb" in a pavement structure as it is loaded at a specific point. The stress bulb, or conical zone, represents the way in which the load application is spread through the pavement system under a steady state or impulse NDT load. The slope of the line that projects through each pavement layer reflects the relative modulus, or stiffness, of the material within the layer, with a fundamental being that as the modulus increases, the stress within the layer is spread over a greater area (*3*).

It is generally accepted that deflections measured far enough away from the center of the load can be used to characterize the subgrade stiffness. As shown in Figure 1, at the distant sensors the pavement surface deflection that is occurring is due only to the stresses or deformations from the subgrade itself, and therefore the outer readings primarily reflect the stiffness of the subgrade soil.

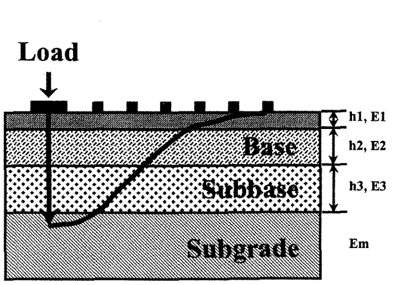

FIGURE 1 Exaggerated deflection basin from FWD.

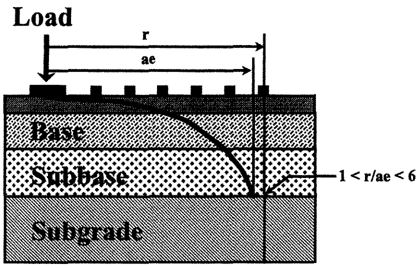

FIGURE 2 Stress "bulb" under FWD load.

As reported in the AASHTO Guide, using deflection measurements collected from the sensor located at a distance of $1 < r/a_e < 6$ (where r is the outer geophone radial distance from the applied load and a_e is the radius of the stress bulb at the interface of the subgrade and bottom layer of the pavement), the subgrade modulus may be estimated from the following equation:

$$E_{sg} = \frac{P S_f}{d_r r} \qquad (1)$$

where

E_{sg} = in situ modulus of elasticity of the subgrade (psi).
P = plate load of the NDT device (lb),
d_r = measured NDT deflection at radial distance r from the center of the plate load (mils),
r = radial distance from plate load center to the point of the deflection measurement (in.) and
S_f = prediction factor based on the soil's Poisson's ratio as shown in Table 2.

Other values for the prediction factor may be obtained from the Guide with the use of a figure that plots the prediction factor versus the radial offset ratio for varying Poisson's ratio values. As the ratio increases the prediction factor also increases until it becomes constant past a ratio of one.

Using this process, the subgrade modulus may be directly estimated without costly computing time and software; however, prediction accuracy may be lost due to the varying nature of subgrade properties.

COMPARISONS

An unprecedented wealth of data on subgrade properties for more than 300 test sections offers many possibilities for the evaluation of subgrade stiffness. The following studies were considered in this analysis:

1. Straightforward comparison between the various moduli estimation procedures (i.e., determining ratios between predicted moduli values from each estimation procedure);

TABLE 2 Prediction Factors Based on Poisson's Ratio

u	S_f
0.50	0.2686
0.45	0.2792
0.40	0.2892
0.35	0.2874
0.30	0.2969

2. Determination of direct relationships between the moduli estimation procedures using regression techniques;
3. Determination of relationships between moduli estimation procedures using regression techniques and including other known properties that influence the resilient modulus; and
4. Development of new procedures to estimate the subgrade moduli on the basis of the subgrade data available.

Results of these studies are provided here to highlight where relationships were and were not found. It is also anticipated that the results noted here may lend insight to those who wish to explore these data further.

Direct Comparisons of Moduli Values from Various Sources

The first comparison explored here was a straightforward comparison using ratios of the various subgrade moduli values. As shown in Table 3, there is a wide range of ratios between the estimated moduli from the AASHTO equation and the backcalculated moduli from the MODULUS program, and between both the backcalculated and estimated moduli and the moduli determined by laboratory testing. The wide scatter of ratios between the backcalculated moduli and the moduli from laboratory testing is consistent with previously published reports and tends to highlight the noted concerns about which values are most appropriate for pavement design purposes (*1,2*).

Regression Analyses Between Various Moduli Sources

Acknowledging that no simple relationship exists, the next step was to explore other relationships that might exist. These studies were conducted by performing linear regression analysis between each of the moduli sources. As one might expect review of ratios mentioned previously revealed no significant relationship between the laboratory and backcalculated moduli. The coefficients of determination (R^2) for this regression analysis did not rise above 0.10, and the root mean square error (RMSE) was generally as large as the moduli values.

Researchers recognized that the relationship between lab and backcalculated moduli must be a function of the subgrade properties, among other things, and expanded the regression analysis to include Atterberg limits, gradations, depth to rigid layer, moisture contents, and other data as available. Even with this additional data, however, a significant relationship could not be found.

One relationship that did prove to be somewhat significant occurred between the estimated and the backcalculated moduli. The estimated value was calculated using Equation 1 and an assumed Poisson's ratio of 0.45. A linear regression analysis of the moduli prediction sources yielded $R^2 = 0.37$ and RMSE = 23,404.

The analysis of estimated versus backcalculated moduli was then expanded to include various subgrade properties in an attempt to improve on this relationship. The inclusion of subgrade properties did improve the relationship, but the results were still somewhat less than favorable ($R^2 = 0.50$, RMSE = 20,949). This is particularly intriguing when one considers that both of these subgrade moduli values are based on essentially the same basic data. From this observation it was established that development of a better estimation procedure may be warranted.

Modification of the Moduli Estimation Equation

Modification of the estimation equation was attempted using a linear regression analysis between the backcalculated moduli and the constant term from Equation 1, $P/d_r r$. The resulting coefficient from this analysis could be used as a new value for S_f. It should be noted that the regression for this particular analysis was performed with the no intercept option, which forces the *y*-intercept through the origin. This analysis procedure produced a new $S_f = 0.1508$ with an R^2 of 0.56 and an RMSE of 20,601. This appears to indicate, at least for the data available, that a slightly improved estimation equation has been formulated with which subgrade moduli can be predicted solely from the seventh sensor deflections and load from NDT.

Predictions of Backcalculated Moduli

As noted previously, use of the equation form shown in the AASHTO Guide for predicting backcalculated subgrade moduli provided reasonable results, but it was believed that a better relationship must exist. To further explore the data, efforts were made to predict the backcalculated moduli using the various data elements noted with a variety of different equation forms.

In initial attempts to establish a relationship no distinctions were made among the various subgrade types. As one might expect, however, the Atterberg limits and gradation information were significant to these relationships. On the basis of this information the sections were sorted and separated by subgrade type to facilitate these analyses. Sections with greater than 50 percent passing the number 200 sieve were considered fine subgrades (clay or silt). The fine subgrades were further distinguished using the plasticity index (PI); subgrades with PIs of greater than 10 were considered clays. Good relationships were ultimately established for each of the three subgrade types in these analyses (clay, silt, and sand). Only seven sections had gravel subgrades, so these sections were not included in

TABLE 3 Direct Comparison Among Moduli from Different Sources

Ratio	Mean	Standard Deviation	Maximum	Minimum
Laboratory / Back calculated	0.57	0.67	10.34	0.01
Estimated / Laboratory	4.65	3.81	58.09	1.10
Estimated / Back calculated	2.34	2.94	36.56	0.20

the analysis. The equations are shown below and the associated statistics are presented in Table 4.

Clay:

$$M_R = 0.88\left(\frac{ld}{S7}\right) + 90.13\left(\frac{b^2}{S7}\right) - 4.88 \times 10^{-3}(b)^2(ld) + 1.47 \times 10^{-4}(sat)^2(ld) - 0.08(b)^2(t)^2 + 116{,}774\left(\frac{b^2}{sat^2}\right) + 94{,}749\left(\frac{t^2}{sat^2}\right) - 2{,}707.99$$

Silt:

$$M_R = 30.17\left(\frac{b^2}{S7^2}\right) + 3.84 \times 10^{-4}(ld^2) + \frac{611{,}120}{spgr} + 630.12\left(\frac{b^2}{t^2}\right) - 23.54\,(b)^2(spgr) + 2{,}439.62\left(\frac{t}{spgr}\right) - 258{,}797$$

Sand:

$$M_R = \frac{-2{,}834{,}967}{dd} + 1.31 \times 10^{-4}(ld)^2(S7) + 15.04(b)^2(S7) + 371.33\left(\frac{dd}{S7}\right) - 3.01 \times 10^{-6}(ld)^2(dd) - 2{,}751.43\left(\frac{t^2}{dd}\right) + 22{,}372$$

where

$S7$ = Sensor 7 reading from FWD (mils),
ld = load from FWD (lb),
t = asphalt or concrete thickness + treated base thickness (in.),
b = untreated granular base thickness (in.),
$spgr$ = specific gravity of the subgrade,
sat = percent saturation, and
dd = dry density of the subgrade.

Common to each of these models is the load and deflection at Sensor 7. Because only Sensor 7 deflection readings were included in this analysis (at a spacing of 60 in. from the load), the distance from the load to the sensor was not needed as a variable. Similarly the area of the loading was constant for each section (using a 12-in.-diameter plate), hence the area also was not a function in the analysis. Variables that did prove significant were the thicknesses of the pavement layers, in situ moisture contents, dry densities, and specific gravities.

Sensitivity Analysis

A simple set of factorial tables was designed using a wide range of input values for each variable to determine the validity of the models. Testing the equation in this way can establish how the equation performs for input values outside the inference space from which it was developed, but still within practical limits. Table 5 presents the ranges used in this analysis.

The model for a sand subgrade appears to yield reasonable values for the backcalculated subgrade moduli for the input ranges considered. Subgrade moduli values generated ranged from 6200 to 153,000 psi. Values greater than 100,000 psi appear high; however, for deflections of 0.25 mils (typically associated with "rock" subgrades) this is not all that surprising.

TABLE 4 Statistics for the Three Subgrade Moduli Prediction Equations

Equation	R^2	Adjusted R^2	Root Mean Square Error
Clay	0.8886	0.8739	6,997
Silt	0.7809	0.7238	11,419
Sand	0.8371	0.8276	15,033

The model for silt seems to falter at the high end of the specific gravity range. Specific gravities in excess of 2.7 tend to produce negative values. This is not a realistic value for specific gravity, however, and if the range of specific gravities is narrowed to a range of around 2.3 to 2.6, moduli generated values begin to appear more consistent with expectations.

The clay model fails at the low end of the percent saturation range. For saturation levels of 10 percent, subgrade moduli values can exceed 700 ksi. Saturation levels of 10 and 20 percent do not seem unreasonable, but they are outside the inference space from which these equations were developed. If the saturation level remains above 30 percent, the equation appears to provide reasonable estimates of backcalculated subgrade moduli.

CONCLUSIONS

The SHRP LTPP program has produced a considerable amount of information characterizing pavement structures. These data were used to attempt to improve existing procedures and develop new procedures to predict subgrade resilient moduli. Equations generated from this analysis can be used to predict subgrade backcalculated resilient moduli based on NDT data and other subgrade properties. These equations have relatively high correlation coefficients (from .78 to .89) and low root mean square errors.

In addition to developing new prediction equations, an attempt was made to redevelop the prediction factor, S_f, used in the AASHTO Guide's subgrade moduli prediction equation. A new factor was established on the basis of the data set with reasonable statistics. It appears that the layer structure has a greater impact on estimations of subgrade moduli than is commonly accepted. However each of the equations generated using all available data were heavily dependent on the layer structure. This could also indicate that Sensor 7 is not sufficiently distant from the load in the SHRP sensor setup.

Evaluations were conducted to explore relationships among the various sources of subgrade moduli. With the volumes of data avail-

TABLE 5 Ranges Used for Sensitivity Analysis

Variable	Range
Load	8,000 - 10,000 (lbs)
Sensor 7	0.25 - 2 (mils)
Untreated Base	4 - 20 (inches)
Treated Base + Asphalt/Concrete	4 - 12 (inches)
Percent Saturation	10 - 100 (%)
Specific Gravity	2 - 3
Dry Density	85 - 115

able one would expect that some relationship between laboratory and backcalculated subgrade moduli could be established; however, these evaluations did not generate any useful relationships.

RECOMMENDATIONS FOR CONTINUING RESEARCH

This limited analysis has raised many opportunities for further research. Some studies that warrant further pursuit are as follows:

- Continue to seek relationships between laboratory and backcalculated subgrade moduli.
- Develop other moduli prediction equations that include subgrade properties but do not include deflection data.
- Continue to pursue a relationship for estimating laboratory subgrade moduli.

Nonlinear modeling or other modeling techniques may be used to better represent these data and the relationships sought. It is evident, however, that the disparity between these methods of estimating subgrade moduli is fairly substantial. Pavement designers should be particularly cautious when estimating subgrade moduli to ensure that the values used are consistent with those on which their pavement design equations are developed.

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