Some Observations About Backcalculation and Use of a Stiff Layer Condition

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For the last several years, advances in estimating layer elastic moduli by the use of pavement surface deflections and backcalculation computer programs have been rapid. As the available computer programs have continued to evolve, so too has the understanding of the input and output of such software. The stiff layer [its location (depth) and stiffness] is, of course, just one of the many important considerations in performing backcalculation of deflection data. Both the traditional and some of the more recent observations pertaining to the various mechanisms that can result in a stiff layer condition, and the effect on layer moduli in backcalculation, are reviewed. Recent project work in the state of Washington reveals that a saturated soil condition or water table can result in a stiff layer condition. Empirical evidence is offered suggesting that saturated soil conditions (or water table) should be considered when evaluating the results of current backcalculation processes.

It is often necessary to include a stiff layer with a semi-infinite depth to achieve reasonable backcalculation results. Traditionally, such layers were believed to be needed either because of a rock layer or stress sensitive materials (*1*,*2*). Recent project work in the state of Washington reveals that a saturated soil condition or water table can cause the same requirement.

The problem of routinely performing backcalculation without recognizing the effects of a stiff layer condition will be illustrated by using a SHRP/LTPP GPS site located in Florida (Figure 1). As is so often the case, no information is available that would suggest a stiff layer condition is apparent; however, results given in Table 1 suggest that inclusion of a stiff layer at a depth of about 6.4 m (21 ft) results in more interesting moduli. This illustrative exercise does not prove anything; however, it is common to observe the inverted moduli seen in Table 1 for the base and subgrade when a stiff layer condition is not used.

Naturally, this raises questions about how to locate the depth of such stiff layers and how stiff they should be. These two questions concerning depth and stiffness (modulus of elasticity, actually) of the stiff layer will be the primary focus of this paper. First, we should further examine the various causes of a stiff layer condition.

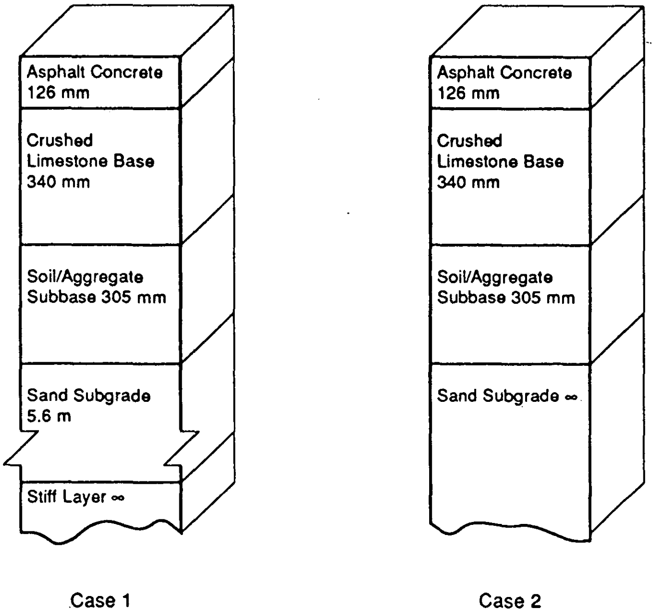
LOAD AND GEOSTATIC STRESSES

The need for stiff layers within the subgrade domain can certainly be due to rock layers or extremely stiff soils such as some glacial tills. However, there may be other conditions, not so immediately apparent, which warrant the use of a stiff layer within the subgrade. First, we should look at some typical stresses in the subgrade due to an applied load and geostatic conditions.

Another LTPP section (GPS 6A, located in Kentucky) will be used to illustrate this (Figure 2). The boring log did suggest a potential stiff layer at a depth of about 5 m (16.5 ft). By use of the ELSYM5 computer program, the vertical and horizontal stresses were estimated under a 40-kN (9,000-lb) load with a 0.69-MPa (100-psi) contact pressure. Two moduli conditions for the Kentucky LTPP section were used as indicated in Table 2.

The geostatic stresses are caused by the weight of the soil. Vertical geostatic stress, σ_v, can be straightforwardly calculated as follows [after Lambe and Whitman (*3*)]:

$$\sigma_v = (z)(\gamma) \tag{1}$$



1 mm = 0.039 in.
1 m = 3.28 ft.

FIGURE 1 SHRP/LTPP GPS-1 pavement section, Florida.

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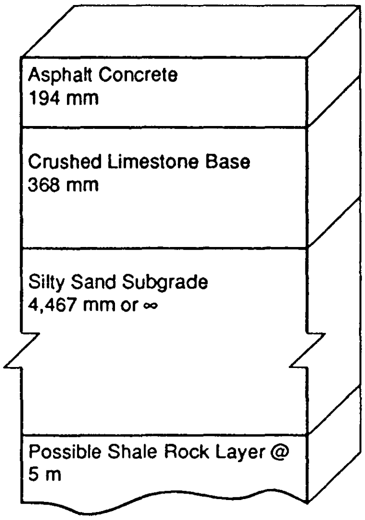
TABLE 1 Load and Deflection Data and Backcalculated Layer Moduli—SHRP/LTPP GPS-1 Pavement Section, Florida

Load = 75.9 kN		
0 mm	–	382.2 μm
203 mm	–	301.5 μm
305 mm	–	257.0 μm
457 mm	–	201.2 μm
610 mm	–	161.5 μm
914 mm	–	105.2 μm
1,524 mm	–	52.3 μm

Layer	Backcalculated Moduli, MPa	
	Case 1 (with stiff layer)	Case 2 (without stiff layer)
AC (21°C)	10,474	13,900
Base	396	216
Combined Subbase/Subgrade	177	239
Stiff Layer @ 6.4 m	*6,895	NA

*Pre-set (fixed) modulus

1 N = 0.225 lbf
1 mm = 0.039 in
1 km = 0.039 mils
1 kPa = 0.145 psi
1 m = 3.28 ft



1 mm = 0.039 in.
1 m = 3.28 ft.

FIGURE 2 SHRP/LTPP GPS-6A pavement section, Kentucky.

TABLE 2 Moduli Cases Used for Kentucky LTPP GPS-6A Pavement Section

Layer	Thickness	Moduli, MPa	
		Case 1	Case 2
AC	194 mm	6895	6895
Base	368 mm	345	621
Subgrade	Case 2 Only 4.5 m	276	207
Stiff Layer	Case 2 Only @ 5.0 m	NA	6895

1 kPa = 0.145 psi
1 mm = 0.39 in
1 m = 3.28 ft

where

σ_v = vertical stress,
z = depth, and
γ = total unit weight of the soil.

Horizontal geostatic stress, σ_h, is related to the vertical geostatic stress by the coefficient of lateral stress, which is designated K:

$$K = \frac{\sigma_h}{\sigma_v} \qquad (2)$$

$K \approx 0.5$ for normally consolidated sedimentary soils but can approach 3 for heavily preloaded soils (overconsolidated). When $K < 1$, $\sigma_v = \sigma_1$ and $\sigma_h = \sigma_3$. When $K > 1$, $\sigma_h = \sigma_1$ and $\sigma_v = \sigma_3$.

The load and geostatic stresses are separately summarized in Table 3. The geostatic stresses tend to be dominant and become fairly large at depths as shallow as 3.0 m (10 ft). Since the geostatic stresses are static, one might discount σ_v; however, σ_h is analogous to σ_3 as used in most triaxial tests for unstabilized pavement materials [such as AASHTO T-274 (*4*)]. Depending on depth and K, σ_h is fairly large as shallow as 1.5 to 3.0 m (60 to 120 in.). The implication is that such stresses combined with stress-sensitive subgrades can result in a high stiffness condition at depth.

This example concerning load and geostatic stresses only illustrates one reason a stiff layer condition is needed for backcalculation of layer moduli. The next question to address is how deep such layers might be, or more specifically, how the depth to a stiff layer can be estimated.

ESTIMATION OF STIFF LAYER DEPTH

Recent literature provides at least two approaches for estimating the depth to stiff layer (*5,6*). Use of either procedure would assume more specific stiff layer indications (say, from a boring log) are not available, which seems to be common. The approach used by Rohde and Scullion (*5*) will be summarized below. There are three reasons for this selection: (*a*) initial verification of the validity of the approach is documented, (*b*) the approach is used in MODULUS 4.0, a backcalculation program widely used in the United States, and (*c*) the approach was adopted for use in the EVERCALC program, results from which will be presented subsequently.

Basic Assumptions and Description

A fundamental assumption is that the measured pavement surface deflection is a result of deformation of the various materials in the applied stress zone; therefore, the measured surface deflection at any distance from the load plate is the direct result of the deflection below a specific depth in the pavement structure (which is determined by the stress zone). This is to say that only the portion of the pavement structure that is stressed contributes to the measured surface deflections. Further, no surface deflection will occur beyond the offset (measured from the load plate) that corresponds to the intercept of the applied stress zone and the stiff layer (the

TABLE 3 Calculated Stresses for Various Depths Beneath the Load—LTPP Kentucky Pavement Section

Load Stress Only

Depth, m	Load Stresses, kPa							
	Case 1				Case 2			
	σ_z	σ_x or σ_y	θ	σ_d	σ_z	σ_x or σ_y	θ	σ_d
1.5	6.2	0.7	7.6	5.5	5.5	0.7	6.9	4.8
3.0	2.1	~0	2.1	2.1	2.8	0.7	4.2	2.1
5.0	1.4	~0	1.4	1.4	2.1	0.7	3.4	1.4
6.1	0.7	~0	0.7	0.7	1.4	~0	1.4	1.4
12.2	~0	~0	~0	~0	~0	~0	~0	~0
25.4	~0	~0	~0	~0	~0	~0	~0	~0

Geostatic Stress Only

Depth, m	Geostatic Stresses, kPa						
	σ_v	σ_h (K = 0.5)	σ_h (K = 3)	K = 0.5		K = 3	
				θ	σ_d	θ	σ_d
1.5	24	12	72	49	12	121	48
3.0	48	23	143	94	24	238	95
5.0	79	40	238	159	39	396	159
6.1	96	48	288	192	48	479	192
12.2	192	96	575	383	96	958	383
25.4	399	199	1196	797	199	1993	797

1 kPa = 0.145 psi
1 m = 3.28 ft

stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which a zero surface deflection occurs. This is shown in Figure 3, where the surface deflection D_c is zero.

An estimate of the depth at which zero deflection occurs can be obtained from a plot of measured surface deflections and the inverse of the corresponding offsets (1/*r*). This is shown in Figure 4. The middle portion of the plot is linear with either end curved due to nonlinearities associated with the upper layers and the subgrade. The zero surface deflection is estimated by extending the linear portion of the D versus 1/*r* plot to D = 0, the 1/*r* intercept being designated as r_0. Because of various pavement section-specific factors, the depth to stiff layer cannot be directly estimated from r_0—additional factors must be considered. To do this, regression equations were developed on the basis of BISAR computer program-generated data for various levels of the following factors: load = 40 kN (9,000 lb), moduli ratios (E_1/E_{sg}, E_2/E_{sg}, and $E_{stiff}/$

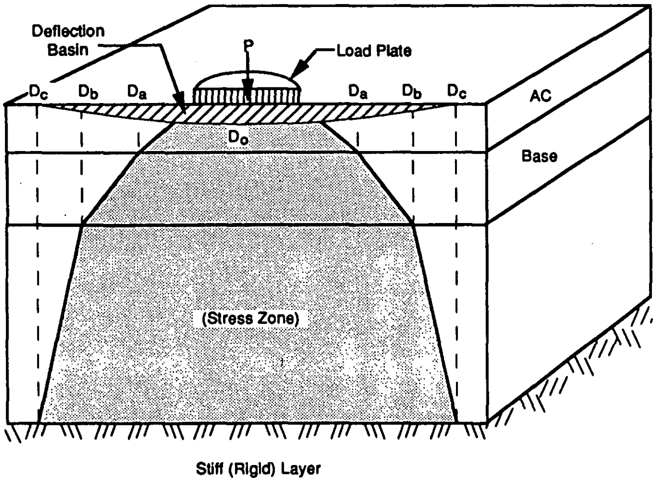


FIGURE 3 Zero deflection due to a stiff layer.

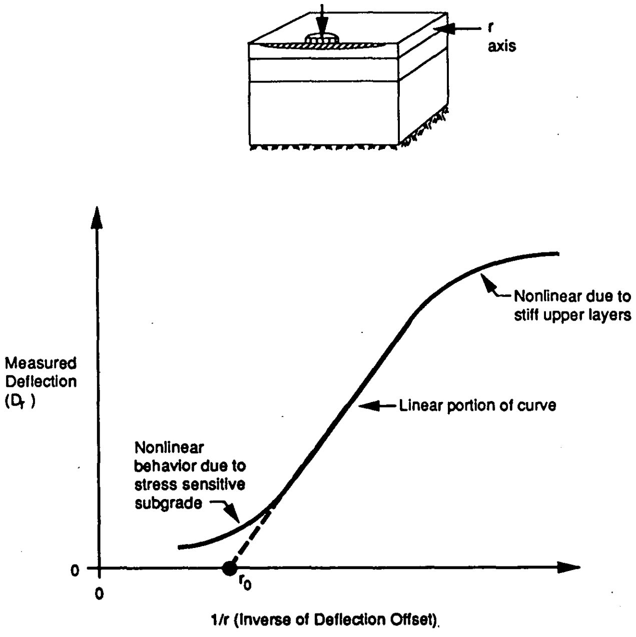


FIGURE 4 Plot of inverse of deflection offset versus measured deflection.

E_{sg}), and layer thicknesses (surface layer, base layer, and depth to stiff layer measured from the pavement surface).

Four separate regression equations were reported by Rohde and Scullion (*5*) for various levels of AC layer thickness. The dependent variable is $1/B$ (where B is the depth to the top of the stiff layer measured from the pavement surface), and the independent variables are r_0 (which is the $1/r$ intercept as shown in Figure 4) and various deflection basin parameters. The equations are as follows: For AC less than 50 mm (2 in.) thick,

$$\frac{1}{B} = 0.0362 - 0.3242(r_0) + 10.2717(r_0^2) - 23.6609(r_0^3) - 0.0037(\mathrm{BCI}) \qquad (3)$$

For AC 50 to 100 mm (2 to 4 in.) thick,

$$\frac{1}{B} = 0.0065 + 0.1652(r_0) + 5.4290(r_0^2) - 11.0026(r_0^3) + 0.0004(\mathrm{BDI}) \qquad (4)$$

For AC 100 to 150 mm (4 to 6 in.) thick,

$$\frac{1}{B} = 0.0413 + 0.9929(r_0) - 0.0012(\mathrm{SCI}) + 0.0063(\mathrm{BDI}) - 0.0778(\mathrm{BCI}) \qquad (5)$$

For AC greater than 150 mm (6 in.) thick,

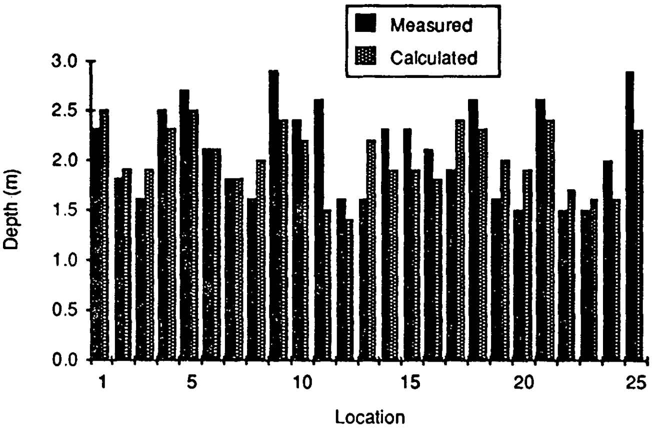
$$\frac{1}{B} = 0.0409 + 0.5669(r_0) + 3.0137(r_0^2) + 0.0033(\mathrm{BDI}) - 0.0665\log(\mathrm{BCI}) \qquad (6)$$

where

r_0 = $1/r$ intercept (extrapolation of the steepest section of the D versus $1/r$ plot) in units of ft^{-1};
SCI = $D_0 - D_{305\ \mathrm{mm}}$ ($D_0 - D_{12\ \mathrm{in.}}$), surface curvature index;
BDI = $D_{305\ \mathrm{mm}} - D_{610\ \mathrm{mm}}$ ($D_{12\ \mathrm{in.}} - D_{24\ \mathrm{in.}}$), base damage index;
BCI = $D_{610\ \mathrm{mm}} - D_{914\ \mathrm{mm}}$ ($D_{24\ \mathrm{in.}} - D_{36\ \mathrm{in.}}$), base curvature index; and
D_i = surface deflections (mils) normalized to a 40-kN (9,000-lb) load at an offset i.

Confirmation of Stiff Layer Depths

Data provided to the authors by B. Mårtensson of RST Sweden AB during 1992 provided the initial confirmation of the Rohde and Scullion (*5*) stiff layer calculation (other than reported by Rohde and Scullion). The results provided by Mårtensson are shown in Figure 5. The road (Route Z-675) is located in south-central Sweden. The field-measured depths were obtained by use of borings and a mechanical hammer. The hammer was used to drive a drill to "refusal" [similar to the standard penetration test (SPT)]. Thus, the measured depths could be bedrock, a large stone, or hard till (glacially deposited material); however, this is an area where rock is commonly encountered at relatively shallow depths. Furthermore, the field-measured depths were obtained independently of the FWD deflection data (time difference of several years).



1 m = 3.28 ft.

FIGURE 5 Plot of measured and calculated depths to stiff layer for Road Z-675 (Sweden).

The FWD deflections were obtained with a KUAB 50 with deflection sensor locations of 0, 200, 300, 450, 600, 900, and 1200 mm (0, 7.9, 11.8, 17.7, 23.6, 35.4, and 47.2 in.) from the center of the load plate. The equations by Rohde and Scullion (*5*) were used to calculate the depth to stiff layer. Since the process requires a 40-kN (9,000-lb) load and 305-mm (1-ft) deflection sensor spacings, the measured deflections were adjusted linearly according to the ratio of the actual load to a 40-kN (9,000-lb) load.

This initial confirmation resulted in the addition of the Rohde and Scullion (*5*) equations to the program EVERCALC, which is the backcalculation software used by WSDOT (*7*). This program, along with data from two pavements located in Washington State, will be used to illustrate that the depth to stiff layer and the stiff layer modulus are both important in obtaining reasonable layer moduli from the backcalculation process. Furthermore, the stiff layer condition appears, at least in some cases, to be strongly influenced by saturated soil conditions (or the water table).

PAVEMENT SECTIONS AND RESULTS

Two pavement sections will be used to illustrate two basic points: (*a*) that the Rohde and Scullion equations appear to estimate the depth to stiff layer for a wider variety of conditions than initially expected and (*b*) that the stiff layer can be "triggered" by saturated soil conditions. The two pavement sections will be separately described, along with the associated results. One section is located at the PACCAR Technical center [about 100 km (60 mi) north of Seattle, Washington] and the other on a state highway (SR-525) located about 25 km (15 mi.) north of Seattle.

PACCAR Technical Center Pavement Section

This test pavement is being used in a joint study between PACCAR, WSDOT, Caltrans, The University of Washington, and the University of California at Berkeley. The flexible pavement is surfaced with 137 mm (5.4 in.) of dense-graded AC (WSDOT Class B) over a 300-mm (13.0-in.) crushed stone base over a sandy clay subgrade. The water table was measured at a depth of 1.7 m (66 in.).

During October 1991, a Dynatest 8000 FWD was used to obtain deflection measurements at 61 separate locations (129 drops). The applied load varied from 21.7 to 63.4 kN (4,874 to 14,527 lb). During testing, the measured average middepth temperature of the AC layer was 20°C (68°F). By use of EVERCALC 3.3, the layer moduli were estimated for various conditions using the previously mentioned layer thicknesses (surface and base) and Poisson's ratios of 0.35 (AC) and 0.40 (base).

Initially, the stiff layer was fixed with a modulus of 6895 MPa (1,000 ksi), and the depth to stiff layer algorithm estimated the top of the stiff layer to be between 1.5 and 1.8 m (60 and 70 in.), which was extremely close to the measured depth of water table. There are no known rock or other major layer transitions within several feet of the surface at this site. As a result, only 31 of the 130 deflection basins resulted in an RMS error convergence of 2.5 percent or less (2.5 percent was used as an acceptable upper limit). Thus, it was decided to try various moduli values for the stiff layer ranging from a low of 69 MPa (10 ksi) to a high of 6895 MPa (1,000 ksi). The resulting layer moduli are given in Table 4 and associated RMS statistics in Table 5.

The results suggest that the stiff layer was "triggered" by the saturated conditions below the water table and, for this condition, a stiff layer modulus of about 276 MPa (40 ksi) is more appropriate than, say, 6895 MPa (1,000 ksi). This observation is based on the RMS and the layer moduli values. For example, the AC modulus of 3885 MPa (563 ksi) corresponds to an expected value of about 4140 MPa (600 ksi) on the basis of laboratory tests for WSDOT Class B mixes—a rather close agreement. The base modulus of 103 MPa (15 ksi) might be a bit low, but the subgrade modulus of 69 MPa (10 ksi) appears to be reasonable.

The effect of using various stiff layer stiffnesses can be illustrated by use of a basic parameter used in mechanistic-empirical pavement design (new or rehabilitation). This parameter is the horizontal tensile strain at the bottom of the AC layer. These strains were calculated for various FWD load levels, backcalculated layer moduli, and three stiff layer modulus conditions with the results shown in Figure 6. Clearly, the estimated strain levels are significantly influenced by the stiff layer modulus condition.

SR-525 Pavement Section

The field data for this pavement section consisted of FWD (Dynatest 8000) deflection basins and boring logs at Mileposts 1.70 and 2.45. This information was obtained from WSDOT production data associated with the normal pavement design process. The FWD testing was done on April 15, 1992, with a measured middepth AC temperature of 7°C (45°F). The condition of the AC layer was variable with various amounts

TABLE 4 Sensitivity of Layer Moduli as a Function of the Stiff Layer Modulus—PACCAR Test Section

	E_{stiff}						
Pavement Layers	69 MPa	173 MPa	276 MPa	345 MPa	518 MPa	690 MPa	6900 MPa
Asphalt Concrete (MPa)*	6100	5713	3885	3284	2795	2539	1960
Crushed Stone Base* (MPa)	17	29	104	138	186	207	290
Fine-grained Subgrade (MPa)*	9908	297	69	59	48	48	37

*Calculated from runs with a RMS% <=2.5%.

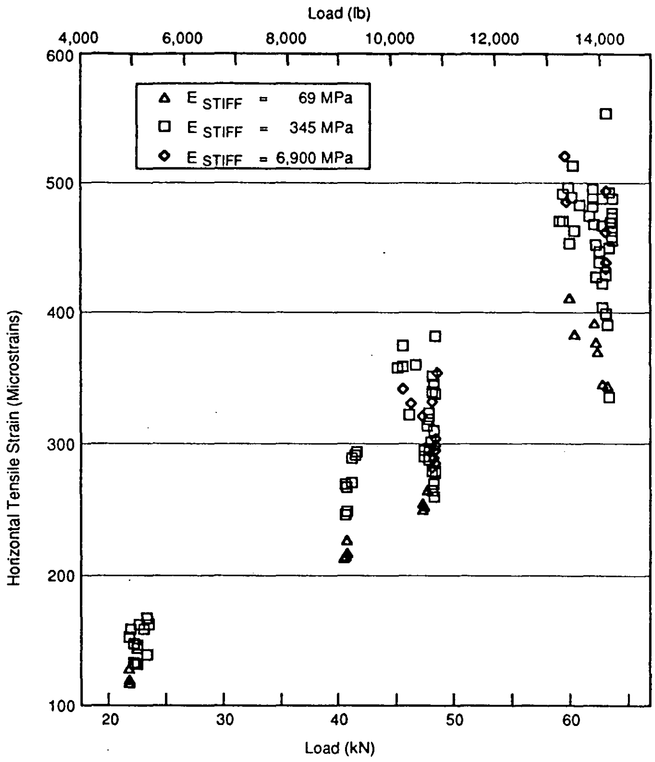
1 kPa = 0.145 psi

TABLE 5 Sensitivity of RMS Values as a Function of the Stiff Layer Modulus—PACCAR Test Section

	E_{stiff}						
RMS (%)	69 MPa	173 MPa	276 MPa	345 MPa	518 MPa	690 MPa	6900 MPa
Mean*	3.0	1.4	1.3	1.7	2.3	2.6	3.8
Standard Deviation*	0.7	0.8	0.9	1.0	1.2	1.3	1.6
Minimum*	1.4	0.4	0.2	0.2	0.6	0.8	1.4
Maximum*	5.6	5.2	6.9	7.5	8.2	8.5	9.4
Total Runs with RMS% <=2.5*	22	113	120	118	80	77	31

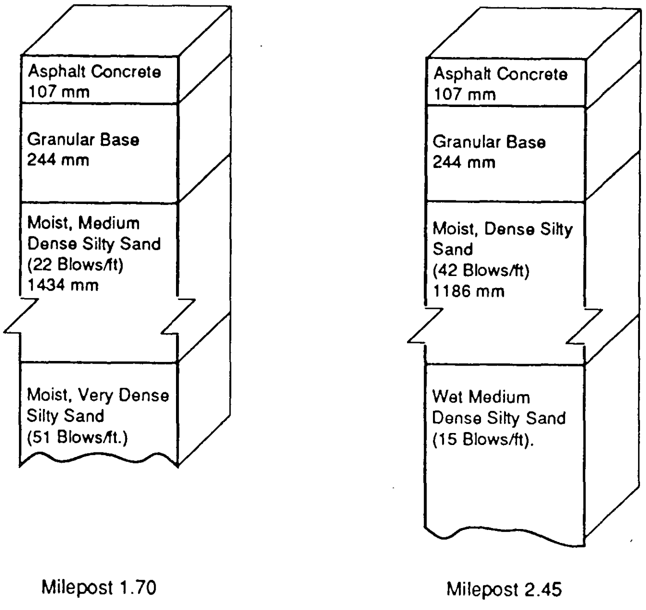
*Calculated for 129 deflection basins.

1 kPa = 0.145 psi



1 kPa = 0.145 psi

FIGURE 6 Calculated horizontal tensile strain versus FWD load for the PACCAR test section.



Milepost 1.70

Milepost 2.45

1 mm = 0.039 in.

FIGURE 7 Cross section for SR-525 pavement sections, MP 1.70 and 2.45.

of fatigue and longitudinal cracking, patching, and minor rutting. The boring logs (summaries of which are shown as Figure 7) indicated no specific water table, but moist/wet conditions were encountered at about 0.9 m (3 ft) (MP 1.70) and 0.6 m (2 ft) (MP 2.45).

The stiff layer algorithm in EVERCALC estimated a stiff layer condition at a depth of 1.8 m (5.9 ft) for MP 1.70. This depth coincides with a transition point from a medium dense sand (22 blows per foot measured by SPT) to a very dense sand (51 blows per foot). The calculated stiff layer for MP 2.45 was 1.5 m (5.0 ft), which coincides with a transition from a moist, dense sand (42 blows per foot) to a wet, medium dense sand (15 blows per foot).

The backcalculated layer moduli, stiff layer moduli, and associated RMS values are given in Tables 6 and 7 for MP 1.70 and 2.45, respectively. The results for MP 1.70 appear to best match the lower stiff layer modulus [345 MPa (50 ksi)]. An AC modulus of about 10 350 MPa (1,500 ksi) would be expected on the basis of uncracked laboratory test conditions. The backcalculated AC modulus is within this range. A visual inspection of the AC condition showed no cracking or rutting at this milepost. The base and subgrade moduli are reasonable, with a low RMS level (1.0 percent average based on four deflection basins). The MP 2.45 section is different. The AC layer exhibited fatigue cracking and rutting, resulting in lower AC moduli. Overall, the lower stiff layer stiffness is preferred; however, the average RMS values (again, based on four deflection basins) are all rather high at this milepost.

TABLE 6 Sensitivity of Layer Moduli as a Function of Stiff Layer Modulus—SR-525 Pavement Section, MP 1.70

Pavement Layers	E_{stiff}	
	345 MPa	6900 MPa
Asphalt Concrete (MPa)*	12177	3472
Crushed Stone Base (MPa)*	232	750
Subgrade (MPa)*	89	52
RMS(%)*	1.0	2.7

*Average of all runs

1 kPa = 0.145 psi

TABLE 7 Sensitivity of Layer Moduli as a Function of Stiff Layer Modulus—SR-525 Pavement Section, MP 2.45

Pavement Layers	E_{stiff}	
	345 MPa	6900 MPa
Asphalt Concrete (MPa)*	2611	1616
Crushed Stone Base (MPa)*	190	280
Subgrade (MPa)*	27	21
RMS(%)*	3.7	5.4

*Average of all runs

1 kPa = 0.145 psi

Only 345 MPa (50 ksi) and 6895 MPa (1,000 ksi) were used as stiff layer moduli for this pavement section. Whereas 345 MPa (50 ksi) provides much better results than 6895 MPa (1,000 ksi), 345 MPa (50 ksi) may not be the optimal value for the stiff layer modulus. Consistent with the intent of this paper, these two moduli values were selected only to demonstrate the potential importance of the influence of saturated soil conditions.

SUMMARY AND CONCLUSIONS

Summary

The goal of this paper was to illustrate and support several basic points:

1. The stiff layer is important,
2. The Rohde and Scullion (*5*) algorithm provides a reasonable estimate of the depth to the stiff layer, and
3. The stiffness of the stiff layer appears to be influenced by saturated soil conditions as well as by the more obvious factors (such as rock and stress sensitivity of the subgrade soils).

These points are offered for the reader's consideration. The authors have proved nothing. They have presented some hopefully interesting empirical evidence.

Conclusions

The backcalculation process is a complicated but powerful tool, which will continue to evolve. Much that we now believe we know about the process is based on empirical evidence. This paper shows that the stiff layer is important in the backcalculation process and that saturated soil conditions (or water table) should be considered in so far as we currently do backcalculation with linear elastic theory. Whereas intuitively this concept seems logical, it is absent in current literature. Thus boring logs and evidence of saturated soil conditions may be more important in production work than generally used today. Furthermore, the issue of identifying such conditions appears to diminish below depths of about 3 m (10 ft).

Continued research on potential inputs to backcalculation (such as boring logs) and new procedures (such as finite element analysis) can only contribute to our improved understanding of the backcalculation process.

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