Considerations of Saturated Soil Conditions in Backcalculation of Pavement Layer Moduli

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The need to account for stiff underlying soil and rock layers has long been recognized in pavement layer modulus backcalculation. Recently, it has been suggested by other researchers that there is a need to separately characterize and incorporate materials below the water table when backcalculating moduli. This discussion is continued by presenting means for determining the depth to the water table and how to assign an appropriate modulus to this material. Results compare the depths to the water table determined by a reflection survey with those obtained by using regression equations developed for deflection testing. It was found that in the case of asphalt concrete over granular base materials, both approaches produced depths close to water table depths in open standpipes. However, there was considerable discrepancy between the depths when the testing was performed on a full-depth asphalt pavement. An appropriate modulus for soil beneath the water table could be determined by minimizing the error between measured and theoretical deflections. It was found that over a time period from fall to spring both the depth to the water table and the modulus of this material did not remain constant. As a result it was concluded that there is a need to determine the depth to the water table and the modulus of the material below the water table each time that deflection testing and deflection analysis are performed.

For a number of years pavement researchers have recognized the importance of accounting for a stiff sublayer when backcalculating the elastic moduli of pavement layers (*1–3*). The presence of such a layer has been attributed to shallow rock formations or to stiff soil layers within about 6 m of the pavement surface. The need to account for the stiff material is often recognized only when there is a poor fit between measured deflection basins and theoretically generated deflections in the backcalculation process. Early in the practice of backcalculation the method used to approach this problem was to assign an arbitrarily high modulus value to a layer at some arbitrary depth if the actual depth was not known. Researchers such as Uddin et al. (*2*) and Rohde et al. (*3*) have devised a means for estimating the depth to the stiff layer based on deflection testing.

Although rock layers and layers of hardened soils definitely constitute stiff underlying materials, it has been argued that saturated soils may respond in a similar, but softer, manner under certain conditions (*4,5*). The discussion of the effects of saturated soil on the backcalculation of layer moduli is continued in this paper. Three methods of determining the depth to the groundwater table (GWT) were tried with data from three pavement test sections at the Minnesota Road Research Project (Mn/ROAD). These included a deflection method, a body wave method, and a method that obtained readings from open standpipes in the test sections. A means of determining the appropriate modulus of material below the GWT is presented, and a comparison is made between backcalculation results assuming a semi-infinite subgrade and those for which the saturated soil is considered to be a separate layer.

A moisture content gradient exists in many soil formations, and it increases with depth to the point of saturation at the GWT or perched groundwater table level, as shown in Figure 1. Provided that there is sufficient time to dissipate the pore water pressure, the material beneath the GWT will behave in a compressible manner when it is subjected to loading since the water will flow into nearby unfilled voids. In this case the response of the soil would indicate that it is soft. The time to dissipate the pore water pressure is a function of the sizes of the voids, the sizes of the soil particles, and the time of loading. Under a dynamic impulse load produced by fast-moving traffic or falling weight deflectometer (FWD), the loading time is very short, which in a well-compacted, fine-grained material will not allow for the dissipation of pore water pressure. Since the bulk modulus of water itself is fairly high compared with the stiffness of soils at relatively low confining pressures the saturated soil behaves as a hard material (*6*). The result will be a reflection of the waves generated by the impulse load from the GWT back to the surface, making it appear as if the material below the GWT is stiff because of its incompressibility. In either case (soft or stiff) the response of the material below the water table would be different from that of the soil above it.

BACKGROUND AND MEANS FOR DETERMINING DEPTH TO SATURATED LAYERS

Deflection Measurement Method

Rohde et al. (*3*) proposed a means of estimating the depth to a rigid underlying layer by the use of regression equations applied to FWD measured deflections. The equations are based on solutions of layered elastic theory involving different thicknesses of asphalt surfacing and depths to a rigid layer. The equations relate the inverse of depth to rigid layer to deflection basin parameters such as surface curvature index, base damage index, and base curvature index as well as a parameter that is determined by the point at which the slope of the steepest portion of the deflection basin intersects a surface displacement of zero. The basis for this approach is that if the subgrade is truly a linear elastic semi-infinite medium, the lower portion of the deflection basin would form a straight line instead of curving up when displacement is plotted against the inverse of the distance from the center of the load, as shown in Figure 2.

The method proposed by Rohde and associates (*3*) is incorporated in the latest versions of the MODULUS (*7*) and EVERCALC (*5*) moduli backcalculation procedures. MODULUS has been adopted as the backcalculation technique of choice for the Long-

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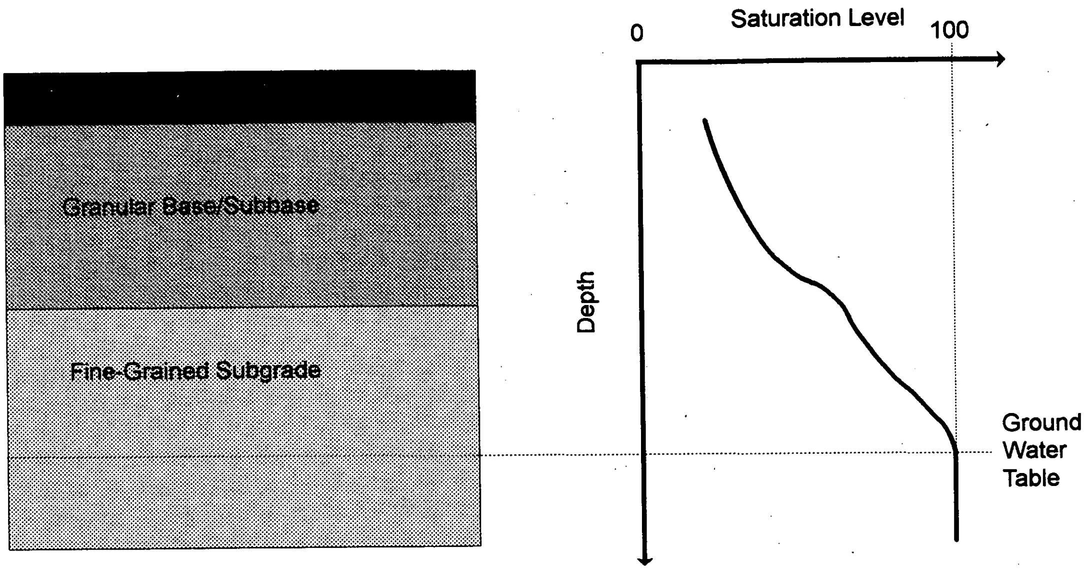


FIGURE 1 **Moisture gradient in pavement over high GWT.**

Term Pavement Performance study initiated by the Strategic Highway Research Program and subsequently continued by FHWA. EVERCALC was developed by the University of Washington for use by the Washington State Department of Transportation.

Mahoney et al. (*4*) reported that this approach to determining the depth to stiff layer worked well in determining the depth to saturated soil, although they cautioned that their results were not conclusive.

Reflection Survey Method

One method used at the Mn/ROAD site to locate the depth to saturated soil involved a geophysical technique known as a reflection survey for analyzing the propagation of surface and reflected waves (*8*). The test setup used to accomplish this is illustrated in Figure 3(*a*). A source (*S*) such as a drop hammer or sledgehammer was used to generate the wave, and an accelerometer was used as a receiver (*R*). The theory for this methodology is described elsewhere (*8*), and a brief summary will be presented.

The wave front of the *P*-wave is hemispherical, as shown in Figure 3(*a*), but ray theory is used to simplify the representation of the traveling waves. This means that the wave path is represented by a ray perpendicular to the wave front and parallel to the direction of wave propagation. Two paths along which the wave energy travels from *S* to *R* can be followed. The direct-wave path on the surface can be described by the travel-time equation

$$t_d = \frac{x}{v_{p1}}$$

where t_d is the travel time of the direct wave and x is the distance between the source and the receiver. The other path is the reflected

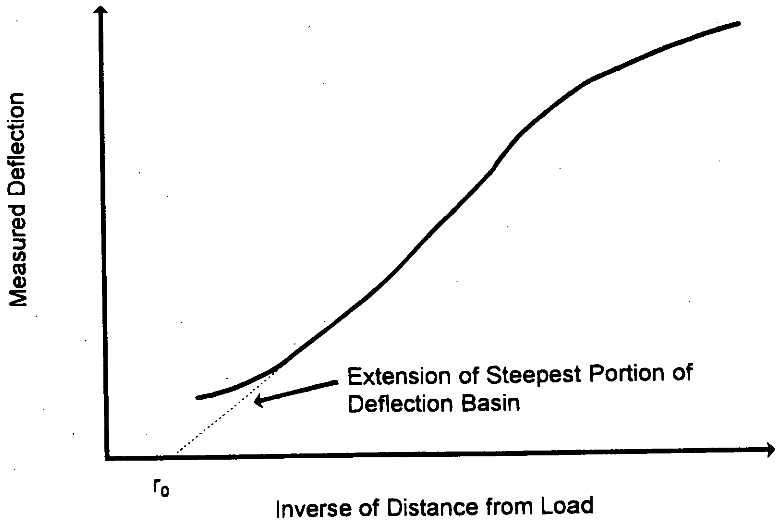
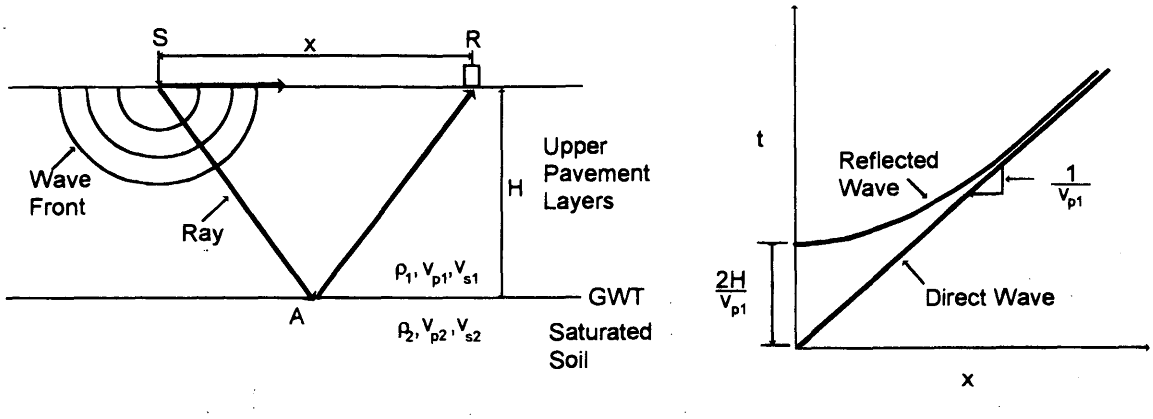


FIGURE 2 **Establishing deflection basin parameter for finding depth to rigid layer (*3*).**



(a) Test Configuration.

(b) Travel-Time Curves.

FIGURE 3 Principles of reflection survey.

wave, and it is composed of the ray from S to the interface A, where material properties change significantly, and back to the surface at R. The reflected wave travel time equation is

$$t_r = \frac{\sqrt{x^2 + 4H^2}}{v_{p1}}$$

Figure 3(*b*) shows the travel-time curves for the direct and reflected waves. For very small values of x, t_r is $2H/v_{p1}$, and for very large values of x, t_r approaches t_d.

To perform a reflection survey, the arrival times for the direct and reflected waves are recorded at the source and at several distances from the source, after which the travel times are plotted. For a layer in which the velocity is not a function of depth, both v_{p1} and H can be found. If v_{p1} is known, H can be solved by using the time difference $\Delta t = t_r - t_d$:

$$H = \frac{1}{2}\sqrt{(\Delta t v_{p1})^2 + 2x\Delta t v_{p1}}$$

A reflection survey can be used to detect the GWT level below a pavement, assuming that the material properties change significantly at that plane. An example of this is shown in Figure 4, in which Δt is determined as a change in the amplitude and frequency of the accelerometer signal.

This approach has limitations, the most important being that the reflected P-wave arrives at the receiver after the receiver has already been excited by the direct waves. This is because the stiff layers in the upper portion of the pavement produce higher velocities for the direct waves. Thus, it is not always easy to distinguish clearly the exact arrival time of the reflected wave. One check that can be made is whether H is greater than the total thickness of the pavement structure, presuming that it is above the water table.

RESEARCH APPROACH

Site Conditions

Data were obtained from three test sections at Mn/ROAD to investigate the effects of saturated soil conditions on the backcalculation of layer moduli. These pavements are designated as TS 1, TS 2, and TS 4, and the structural sections are shown in Figure 5. Each test section is approximately 150 m in length. TS 1 and TS 2 are asphalt concrete (AC) over a granular base, whereas TS 4 is a full-depth asphalt pavement. The geology of the site is such that there are no rock ledges or very stiff soil layers down to a depth of at least 30 m. The subgrade soil is characterized as being a highly plastic silty clay. The water table in this portion of the Mn/ROAD facility is high because of a nearby retention pond that has had water in it since the start of roadway construction. Each Mn/ROAD section has an open standpipe located approximately in the center of the test section offset in the shoulder 5.7 m from the centerline of the roadway.

Testing

Deflection testing was accomplished with a Dynatest Model 8000 FWD in the fall of 1993 and spring of 1994. Deflection measurements were normalized to a 40-kN load for the purposes of presenting these results. Backcalculation of layer moduli was performed by using EVERCALC version 3.3. The actual plan thicknesses of the asphalt concrete and granular base and subbase layers were used in the backcalculation process. For asphalt concrete over granular base and subbase layers, no attempt was made to subdivide the subgrade beyond differentiating the depth to the water table. In the full-depth pavement previous research (*9*) has indicated the need to consider the top portion of the subgrade to a depth of 1140 mm as a separate layer to account for the vertical variation in subgrade modulus.

Reflection surveys of the test sections were performed in the fall of 1993 by the techniques described above. At the same time readings from open standpipes were taken to make comparisons.

RESULTS

Depth to Saturated Layer

Comparisons of the three methods for determining the depth to the saturated layer are presented in Figure 6. The agreement between these techniques is excellent in TS 1, in which all three methods indicated a depth of between 1.8 and 2.0 m for the saturated layer. In TS 2 the reflection survey predicted the depth to be about 2.3 m, whereas the deflection method estimated it to be at about 1.9 m and the standpipe reading was 1.6 m. The largest disparity in the results

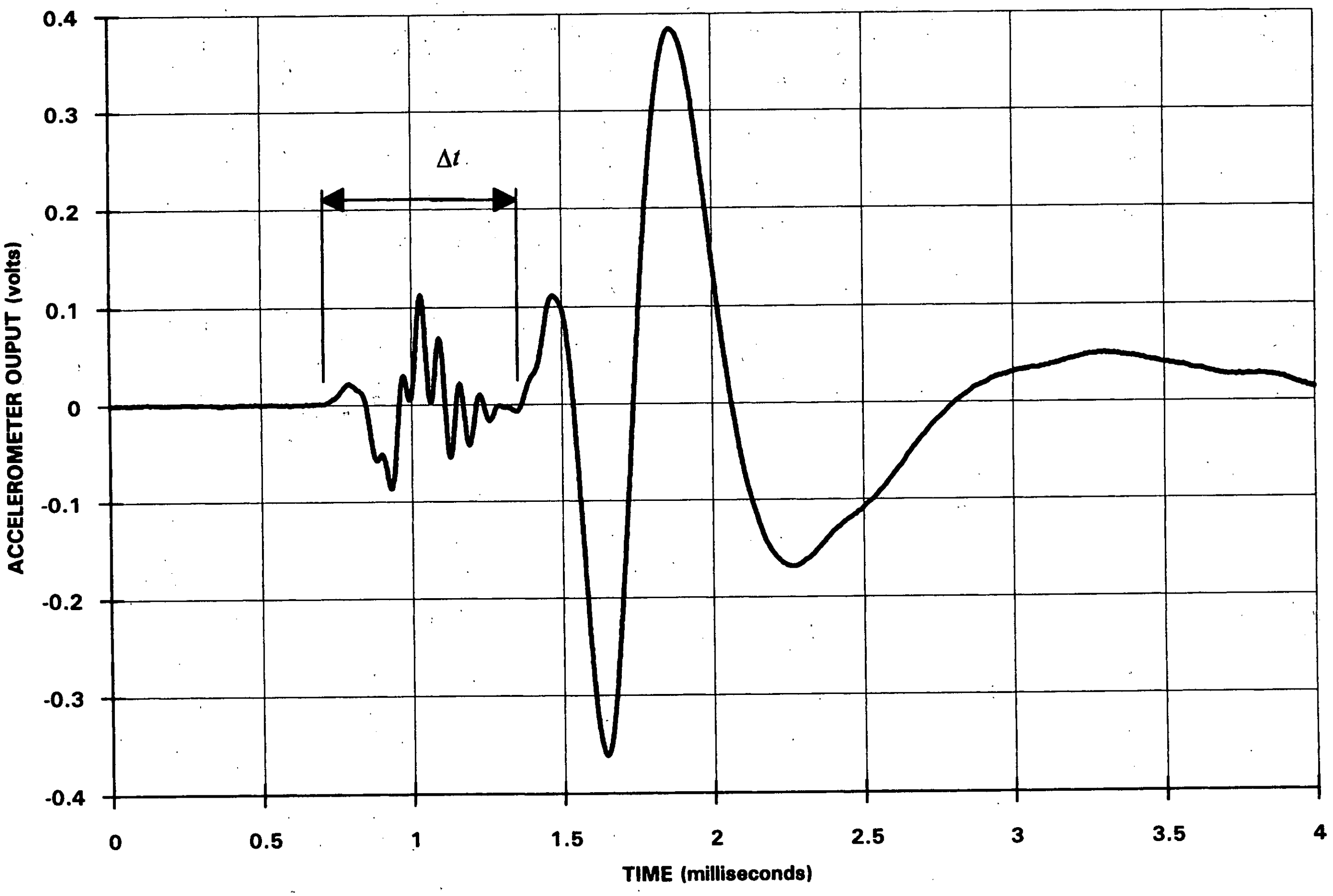


FIGURE 4 **Example of accelerometer output from reflection survey.**

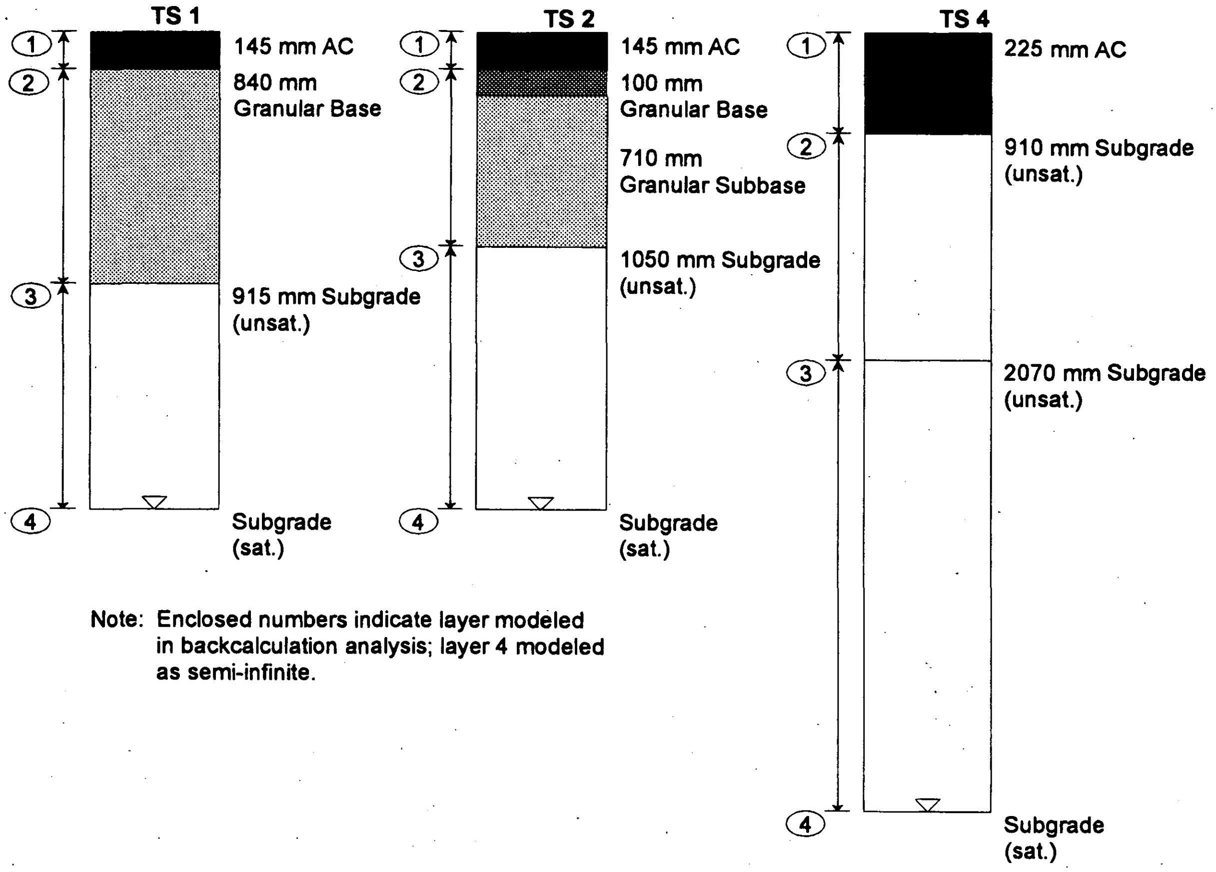


FIGURE 5 Pavement structures and layer configurations investigated at Mn/ROAD.

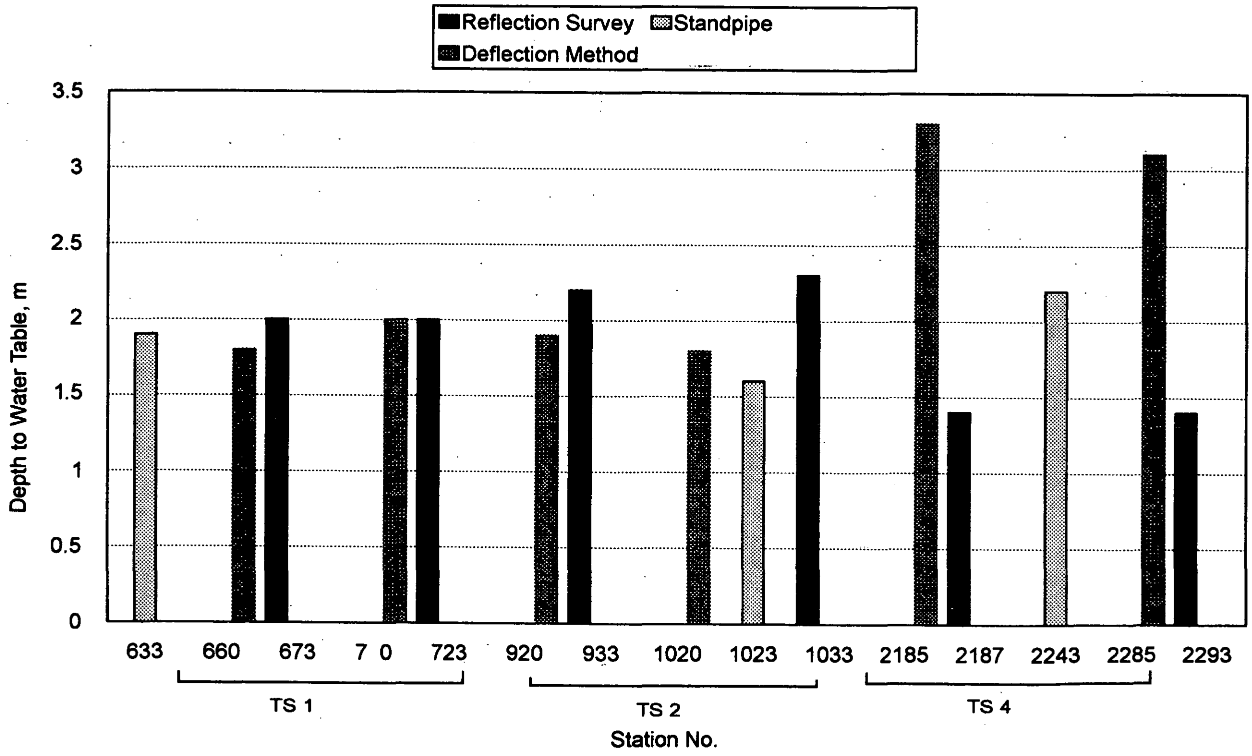


FIGURE 6 Comparison of depths to water table.

occurred in TS 4, in which the equations of Rohde et al. (*3*) put the GWT at 3.2 m and the reflection survey technique suggests that it is at 1.4 m, with the standpipe indicating 2.2 m.

Although some rather large differences may be noted for the different techniques used to estimate the depth to a saturated soil condition, it is encouraging that all three detected a condition of saturated soils near the surface. The differences might be explained both in terms of location and test methods. It should be pointed out that the difference in locations for the FWD test points and the observation wells were in excess of 15 m in some instances, although the difference in locations for the FWD and reflection surveys were all less than 4 m. In TS 4, in which the largest difference between the deflection and reflection survey methods occurred, it is perhaps the nonlinear response of the subgrade that is responsible for the difference. The reflection survey was carried out with a light hammer, and the response of the subgrade may have been relatively stiff in this instance compared with that from the heavy FWD load; thus, the stiff layer appeared to be closer to the surface. It should be remembered that TS 4 is a full-depth asphalt concrete section, so the subgrade was much shallower in this pavement, which means that the nonlinearity of the soil is more prominent in the results.

To investigate how the depth to the stiff layer might change with time, the approach that used the equations of Rohde et al. (*3*) was applied to data gathered in the spring of 1994 at the same test locations. The data in Table 1 show how the depth to saturated conditions changed between the fall and spring. It can be seen that the depth increased for TS 1 and TS 2 but decreased for TS 4. This coincided with increased in situ moisture content readings taken with time domain reflectometers (TDRs) during the same time periods for TS 2 and TS 4. The implication from this is that the depth to GWT or perched GWT is not necessarily constant and that it should be determined each time that deflection testing is performed on a pavement.

Effects on Backcalculation

Since saturated soil will not behave in the same manner as a very stiff layer such as a rock ledge, the appropriate modulus for this layer must be determined. This can be done by isolating the saturated layer during the backcalculation analysis. Two different backcalculation approaches were used for the three test sections, as shown in Figure 5. In the first approach the presence of the saturated layer was neglected so that a three-layer system was being modeled. For the second approach the medium below the calculated depth to the GWT was modeled as semi-infinite; the configurations of the upper three layers were the same as those for the first approach. The modulus of the (saturated) half-space was determined by allowing the modulus value to vary over a range of fixed values, whereas the moduli of the upper layers were left as open parameters. The best estimate for the modulus of the saturated layer was taken to be the one that returned the minimum error between the backcalculated and measured deflections. In the present study, the measure used was the root mean square (RMS) error, and its significance is discussed elsewhere (*10*). It is considered desirable to achieve a fit between measured and theoretical deflections such that the RMS error is less than 1 percent. Figure 7 shows how the RMS changed with the modulus used for the saturated layer for one of the test points in TS 4. In this case the saturated layer modulus for the minimum RMS was about 105 MPa. By using this approach to identify the modulus of the saturated layer, a comparison was made between moduli backcalculated by a normal blind technique in which the subgrade is considered a semi-infinite half-space and one in which the depth to and modulus of the saturated layer are taken into account.

Table 2 provides the results of the backcalculation comparisons. In almost every instance some reduction of the RMS occurred when the saturated layer was considered separately. This improvement in the fit ranged from relatively small (0.03 percent) to moderate (0.53 percent). The reader may note that the backcalculated modulus values of the granular pavement layers are consistently lower than those of the subgrade, particularly in the fall of 1993. At first this may seem strange, but some discussion of why this may have occurred should help to explain why this is not as unreasonable as it seems. First, the thicknesses of the base layers in TS 1 and TS 2 are substantial (840 and 810 mm, respectively), as shown in Figure 5. The calculated bulk stress at the midpoint of these base thicknesses is relatively low at less than 35 kPa. When this value is used in constitutive equations developed for laboratory-tested granular materials at Mn/ROAD (*11*), the predicted modulus of the granular materials is about 95 MPa, which compares well with the values for Layer 2 given in Table 2. Likewise, the deviatoric stress at the top of the subgrade is very small (less than 14 kPa). An examination of laboratory results showed that at this level of deviator stress the subgrade had a resilient modulus of about 152 MPa at optimum moisture content and one of about 97 MPa at a moisture content 2 percent over the optimum (*11*). Again, when compared with the laboratory-determined values, the backcalculated subgrade moduli are not unreasonable. In the fall there were instances of extremely high subgrade moduli, but the soil was dry during this time of year, so it could be expected to be stiffer.

TABLE 1 Changes in Depth to GWT with Time

Test Section	Station No.	Depth to Saturated Soil, m	
		Fall 1993	Spring 1994
1	660	1.7	2.2
	710	2.0	2.4
2	920	1.9	2.3
	1020	1.8	2.2
4	2185	3.3	2.8
	2285	3.1	3.0

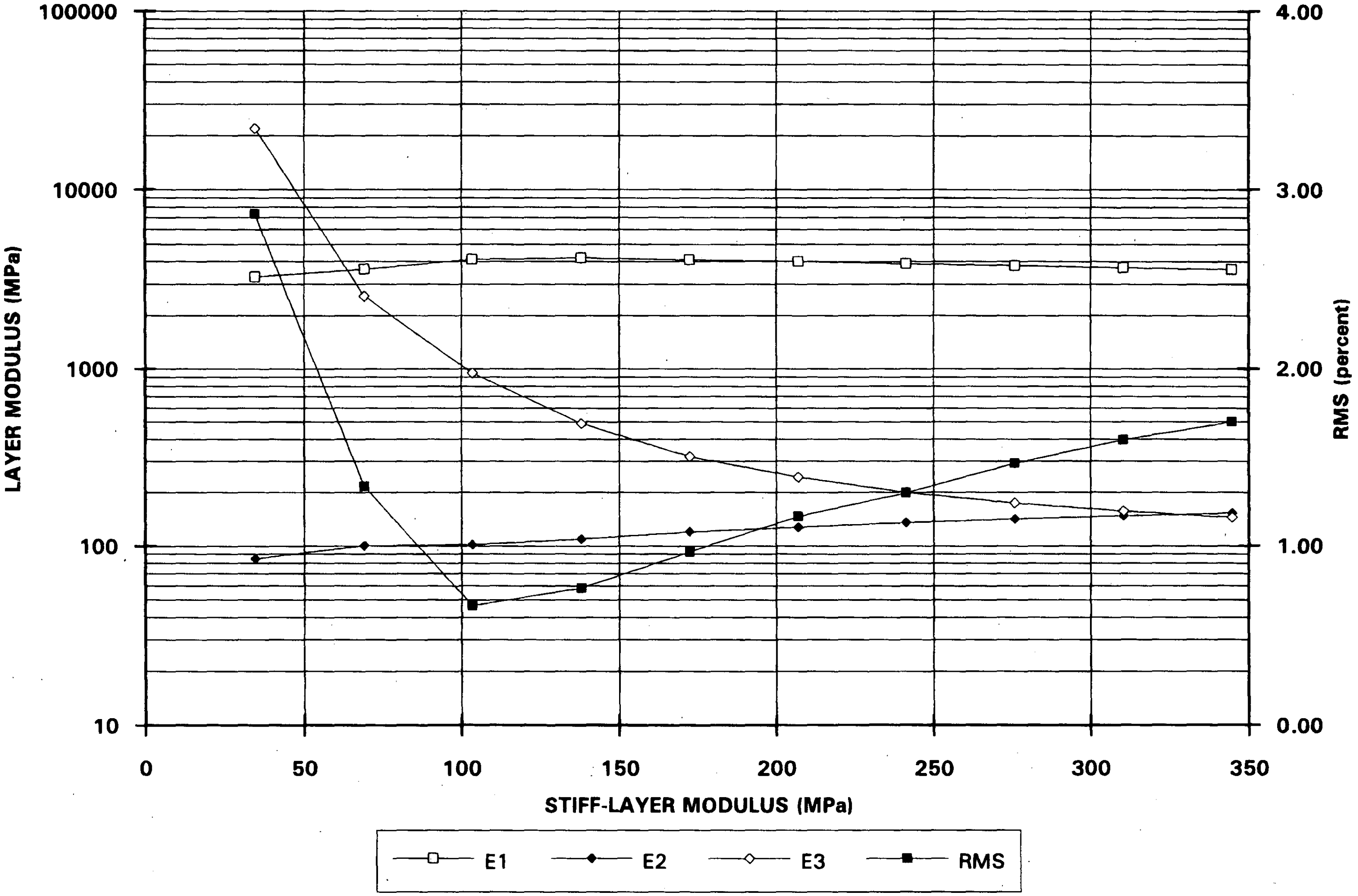


FIGURE 7 Variation in layer moduli and RMS with fixed saturated layer modulus.

TABLE 2 Results of Backcalculation

Test Section	Station No.	Date	Account for Sat. Layer?	Layer Moduli, MPa				RMS
				E_1	E_2	E_3	E_4	
1	660	Fall 93	Yes	3397	93	391	172	0.60
			No	3036	105	194		1.03
	710	Fall 93	Yes	4259	107	169	207	0.40
			No	4404	102	197		0.33
2	920	Fall 93	Yes	4956	92	395	172	0.37
			No	4407	108	200		0.40
		Spring 94	Yes	6881	154	81	345	0.77
			No	9299	103	197		0.80
	1020	Fall 93	Yes	3907	94	287	172	0.57
			No	3603	104	188		0.93
		Spring 94	Yes	6037	141	76	345	0.87
			No	8214	94	199		1.10
4	2185	Fall 93	Yes	4111	102	951	103	0.67
			No	3944	132	222		1.20
		Spring 94	Yes	7453	85	160	276	0.93
			No	7782	75	232		1.03
	2285	Fall 93	Yes	3982	102	646	138	0.67
			No	3615	127	224		0.87
		Spring 94	Yes	6793	101	136	276	0.73
			No	7265	84	213		1.10

It should also be noted that the stiffness of the saturated layer did not remain constant from the fall to the spring. In TS 2 the saturated layer stiffness increased from 172 MPa in the fall to 345 MPa in the spring, whereas in TS 4 it increased from 120 to 276 MPa. As mentioned earlier this coincides with increased in situ moisture content measurements made with TDR probes. There is a suggestion that the stiffness of the material in the saturated layer does not remain constant over time, so that in addition to determining the depth to the stiff layer, the modulus of the stiff layer should also be backcalculated each time that deflections are measured.

SUMMARY

Accounting for the saturated layer is important in the backcalculation process to better represent the structural section of pavements. The properties of this layer may differ significantly, being either stiffer or softer, from those of the overlying soil. Locating the depth of the saturated layer in areas where reliable water table level data are not available may be done by either reflection survey or by the method of Rohde et al. (*3*). It seems that some refinement may be needed in both of these methods to obtain reliable agreement with observation well data. The reflection survey technique uses a low impulse load, which may cause conditions not representative of those under traffic. On the other hand the equations of Rohde et al. (*3*) were developed for a very stiff layer (6900 MPa), so they are outside of their limits when considering saturated materials with moduli on the order of 345 MPa. The stiffness of the saturated layer should be varied to investigate which modulus value minimizes the error between measured and theoretical deflection basins.

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