Nondestructive Testing with Falling Weight Deflectometer on Whole and Broken Asphalt Concrete Pavements

FRIEDRICH W. JUNG AND DIETER F. E. STOLLE

Extensive testing of flexible pavements with the falling weight deflectometer on various test sites in Ontario has aided the development of a rational method of deflection basin interpretation. The goal is a fast computer program (PROBE) that calculates important mechanistic response parameters and determines the quality of data and the degree of structural integrity of the pavement layers. Using the theory of Boussinesq and Odemark's method of equivalent layer thickness, two quantities are defined to help interpret deflection bowl data: (a) the effective modulus of measured surface deflection and (b) the effective modulus of subgrade deflection. Both moduli change with their radial distance from the test load. When plotted they may briefly be referred to as the surface modulus profile and the subgrade modulus profile, respectively. Both moduli provide apparent values of elastic stiffnesses, using uniform elastic half-space solutions. They are parameters for a systematic study of the difference between the theoretically expected and the observed behavior of asphalt concrete pavements. The surface modulus profile evaluates the quality and integrity of pavement layers. Both the surface and subgrade modulus profile are used to estimate the subgrade modulus near the test load, which is the base for further calculations of primary response parameters by the Odemark method. Examples are presented, ranging from very good to poor and broken conditions. Computer simulations with various programs suggest two major points: (a) dynamic effects have only a comparatively minor influence, so that elastostatic modeling appears to be feasible; and (b) deflections die away faster than expected with radial distance, probably because of an increase in the subgrade modulus with depth, an unrecorded presence of a bedrock face, or—more likely—discontinuities of unbound or cracked layer materials. In short, the new approach tries to obtain information and interpretations on system features of field cases by systematically studying the deviation from simple elastostatic modeling.

Owing to the popular use of the falling weight deflectometer (FWD), a great deal of effort has gone into interpreting FWD-generated deflection data. Such efforts have mainly centered around the backcalculation of layer material properties within the framework of continuum mechanics, in particular, the elastic layer theory.

This theory, however, implies that a certain condition be met, namely that the pavement layers are continuous and are not broken or cracked, or that at least the FWD test is carried out on a spot of unbroken or uncracked pavement. Continuum mechanics assumes continuous layer materials and cannot describe cracked or broken pavements. Unfortunately, this fact has diminished the usefulness of backcalculated results. For this reason more emphasis should be placed on interpretation rather than on backcalculation.

Many tests in Ontario have been carried out on flexible pavements that were severely cracked or broken, and it was found that no elastostatic analysis method could interpret the results. Such experience with respect to analyzing data, gathered at severely damaged sections, has confirmed the inappropriateness of using elastic theories in the usual way. Therefore, an alternative backcalculation and interpretation methodology has been investigated. Instead of emphasizing more realistic modeling of the boundary value problem, the new approach, incorporated into the new PROBE program, uses differences between the real problem and the idealized problem, to estimate a "weighted average" of in situ properties and to obtain other important information on the integrity and the state of deterioration of layer materials.

EFFECTIVE MODULUS OF MEASURED SURFACE DEFLECTION

The FWD is an instrument that measures the peaks of a deflection wave from an impulse load created by a falling weight. The test load is distributed over a circular contact pressure area 300 mm in diameter and thus resembles, also in its duration in time, a passing heavy single-tire wheel load from a truck. An essential feature is that the peak deflections, measured at various distances from the load, superficially resemble the deflections created by a corresponding elastostatic load.

The first step of the new approach is to assume that the FWD-generated deflections correspond to elastostatic deflections on a uniform elastic half space. Then, to interpret the data, effective moduli are calculated that are apparent, but well-defined, values of surface stiffness.

Definition

The effective modulus of measured surface deflection of a flexible pavement in an FWD test is defined as follows: it is the modulus that a uniform elastic half space would have under a corresponding static load, having the same deflection as measured by the FWD sensor, at the same distance from

F. W. Jung, Pavements and Roadway Office, Research and Development Branch, Ministry of Transport of Ontario, Downsview, Ontario, Canada. M3M 1J8. D. F. E. Stolle, Department of Civil Engineering and Engineering Mechanics, McMaster University, Hamilton, Ontario, Canada L8S 4L7.

the load axis on a layered flexible pavement. This term is sometimes called the surface modulus. It is a function of the distance from the load axis.

Derivation

The concept is derived from a paper by Yoder and Witczak (*1*, p.29), which contains an equation for the vertical deflections in a uniform elastic half space, loaded by a circular distributed load. For the surface deflections ($Z = 0$) the equation can be written as follows:

$$Y = P(1 - \mu^2)A\ H/E \tag{1}$$

where

- Y = vertical surface deflection,
- P = contact pressure (force per unit area),
- μ = Poisson's ratio (assumed to be 0.35),
- A = radius of loaded area,
- E = modulus of linear elastic material,
- H = a function of ratio X/A, and
- X = distance from load axis.

Solving Equation 1 for E, one obtains the function of the effective modulus of surface deflection, E_x, in which the deflections, Y, are now regarded as the result of FWD deflection measurements.

$$E_x = P(1 - \mu^2)A\ H/Y \tag{2}$$

Note that for distant deflections ($X > 5A$) the factor, H, merges into $H = A/X$. This means Equation 1 becomes identical to the Boussinesq equation for a concentrated load, L (with $L = \pi P A^2$), and Equation 2 is then identical to the one offered by Ullidtz (*2*).

Characteristics of Surface Modulus Profile, E_x

Characteristics of the surface modulus profile are illustrated in Figures 1 through 6 and have been drawn after studying many field tests of flexible pavements in Ontario; in the figures, X is the point of FWD measurement. The following features have been observed:

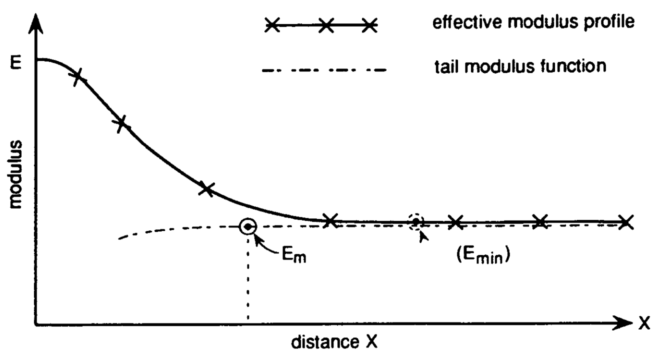

FIGURE 1 Effective and tail modulus for elastic layer systems.

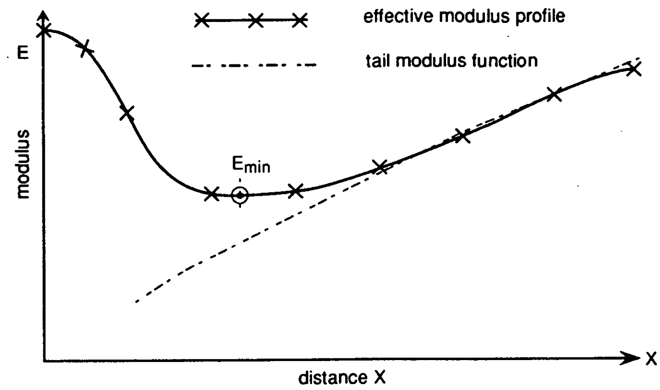

FIGURE 2 Effective and tail modulus for whole AC pavements.

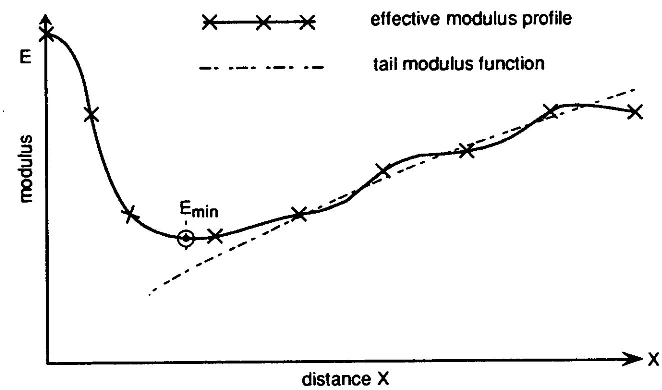

FIGURE 3 Effective and tail modulus for cracked AC pavements.

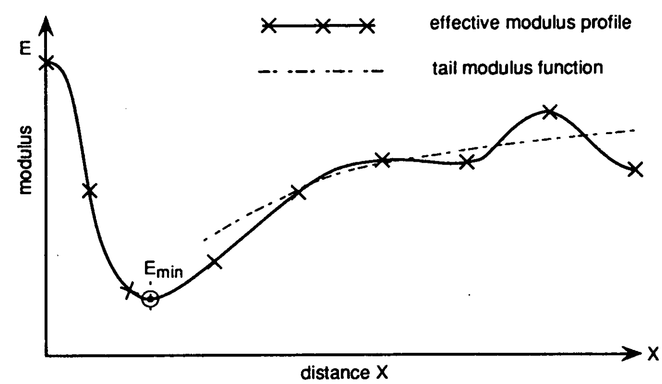

FIGURE 4 Effective and tail modulus for broken AC pavements.

1. Near the load, the stiffening effect of the upper structural layers is strongest, and the effective modulus is large, because at and around the load position the effective modulus represents the overall stiffness of all the pavement layers.

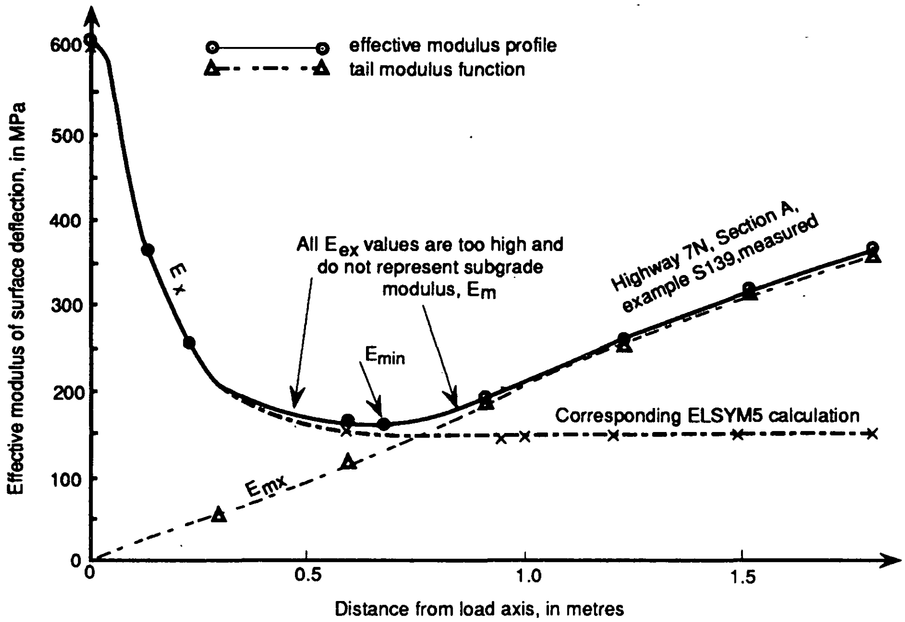

FIGURE 5 Concept of effective modulus of surface deflection: Highway 7N, Section A example.

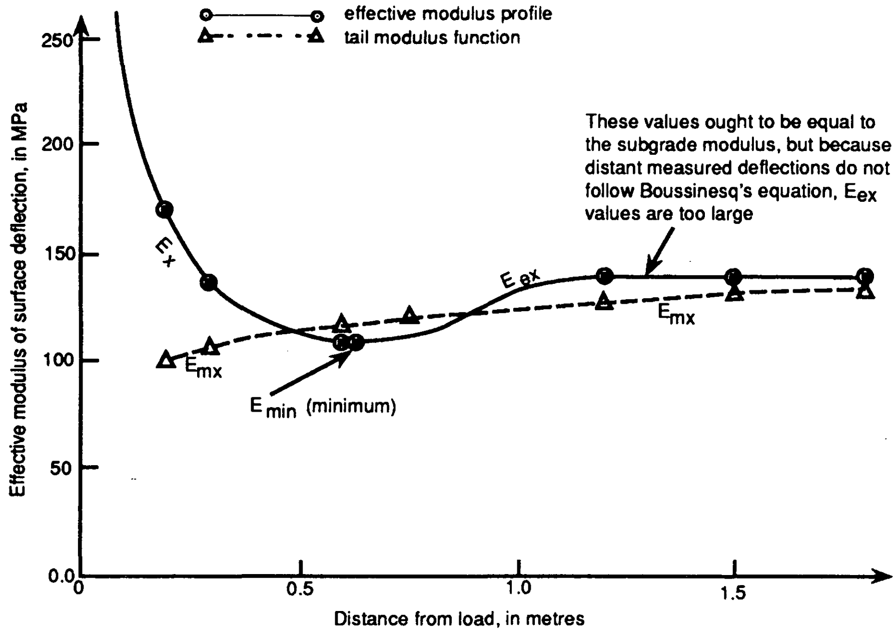

FIGURE 6 Concept of effective modulus of surface deflection: Highway 7N, test pit example, Highway 80 Near Sarnia, 1989, partly broken AC.

2. When using computer-generated data (ELSYM5) of a layered pavement structure, for linearly elastic materials and for an "infinitely" deep subgrade with constant elastic stiffness, the distant tail of the effective modulus profile merges into a horizontal asymptote at the level of the subgrade modulus, E_m, as shown in Figure 1.

3. When using real data from the tested flexible pavements, this asymptote is not horizontal any more, but becomes a line or curve with a positive gradient, as illustrated in Figures 2 through 5. The reason is that the measured deflections die away faster with increasing distance than the elastostatic model would allow. A faster decrease in deflections means an increase in the computed surface modulus values.

4. Because of the characteristics in Items 1 and 3 on all field-tested flexible pavements, the profile of the effective modulus of surface deflection has a minimum, usually not too far from the load (within a meter or less). The location of the minimum signifies that the stiffening effect of the upper layers

has faded away, and the stiffness at and beyond this distance is determined by the subgrade.

5. The magnitude of this minimum value of the effective modulus and its distance from the load axis both have been observed to diminish with a decrease in pavement integrity, or wholeness, usually manifested by cracks.

6. On flexible pavements of good or fair condition (Figures 2, 3, and 5) the distant values of the effective moduli are located on a line or curve that can be called the tail modulus function. On pavements in severely cracked or broken condition, the tail modulus function cannot be determined (Figure 4). The tail modulus function is discussed next.

Quality Indicators from Curve Fitting of Tail Modulus Function

The tail modulus function, E_{mx}, is derived by modifying Equation 8 from Jung (*3*):

$$E_{mx} = \frac{P\,A^2(1 - \mu^2)X^{(\eta - 1)}}{\zeta} = C \cdot X^{(\eta - 1)} \tag{3}$$

where

E_{mx} = tail modulus function, as established below;
A = radius of contact pressure area;
C = constant;
X = distance from load; and
η, ζ = constants found by curve-fitting deflection data (*3*).

In the earlier version of PROBE that is based on consistency tests on data collected in Ontario (*3,4*), the value of the tail modulus function, at X_t = 0.75 m, was considered an approximation of the subgrade modulus, E_m, valid at and around the test load. This approximation yielded consistent results on various test sections in Ontario, although values often are too high.

A comparison with MODULUS, a layer analysis program developed in Texas, was important. The modulus, E_m, as calculated by the original PROBE program (Equations 3 and 4 with $X = X_t = 0.75$), compares well with the subgrade modulus computed by MODULUS in Lytton et al. (*5*, p.77). The comparison is illustrated in Figure 7. The values E_4, from the MODULUS program, are about 10 to 25 percent larger than the values E_m. The correlation coefficient of the linear regression analysis for 21 reliable data points (out of 25 total) is $r = 0.984$.

In the current version of PROBE, the curve fitting is carried out by linear regression analysis of the logarithms of Equation 3:

$$\log E_{mx} = \log C + (\eta - 1)\log X \tag{4}$$

To establish the constants, C and η, with some confidence, three or four valid points from the tail of the deflection basin are needed.

In the current version of the PROBE program, poor quality of pavement is indicated by a group of information items, such as

1. The number and the location of sensor readings discarded at the tail of the basic (for instance, two values at 1.5 m and 1.8 m in the case of broken pavement),

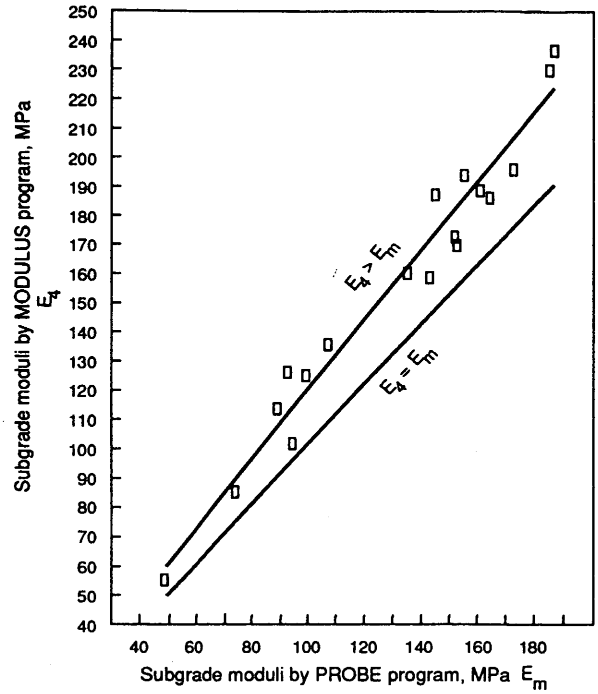

FIGURE 7 Comparison of subgrade moduli [21 points (*5*)].

2. Several deflection sensor readings with large errors of fit (errors of fit >10 percent),
3. A large value of η(>2.5), and
4. Low correlation coefficient (<0.85).

All four items should be considered. The correlation coefficient is the last and the weakest criterion because it is optimized by discarding sensor locations that exhibit too large an error of fit.

EFFECTIVE MODULUS OF SUBGRADE DEFLECTION

The effective modulus of subgrade deflection is derived from Boussinesq's equation for vertical deflections in a uniform half space at the depth $Z = H_{em}$.

$$E_{mz} = \frac{P(1 - \mu^2)\,A^2}{XY_s}\left[\frac{1}{\sqrt{1 + \left(\frac{z}{x}\right)^2}} + \frac{\left(\frac{z}{x}\right)^2}{2(1 - \mu)\left(\sqrt{1 + \left(\frac{z}{x}\right)^2}\right)^3}\right] \tag{5}$$

where

E_{mz} = subgrade modulus profile, effective modulus of subgrade deflection (MPa);

$Z = \Sigma H_{em}$ = sum of equivalent layer thicknesses, with respect to subgrade modulus; and
Y_s = vertical deflection on top of subgrade (mm) (refer to Equation 6).

$$Y_s = Y\left[1 - (1 - K) \cdot \frac{E_m}{E_{1\text{eff}}} \cdot \frac{H_1 + H_2 + H_3}{Z}\right] \qquad (6)$$

where

K = expression in square bracket of Equation 5,
E_m = subgrade modulus,
$E_{1\text{eff}}$ = combined effective modulus of upper layers, and
$H_1 + H_2 + H_3$ = sum of thicknesses of upper layers.

Equation 6 is an approximate correction for establishing the deflection on top of the subgrade, Y_s. The value Y_s (unknown) is computed from the measured surface deflection (Y).

By means of an iterative procedure, Equations 5 and 6 are used to calculate the subgrade modulus profile, E_{mz}, which is similarly defined as the surface modulus profile, E_x. The E_{mz} profile has its lowest value under the test load and starts with a horizontal tangent. In normal flexible pavements (asphaltic concrete and unbound granular bases), the E_{mz} profile increases with radial distance, X, from the test load, and the gradient of this increase is steeper for cracked and broken pavements. For continuous elastic materials (such as portland cement concrete on cement-treated bases) the E_{mz} profile is virtually a horizontal straight line. Thus, the shape of the E_{mz} profile was found to be indicative of material characteristics.

However, the main purpose of this profile is to estimate a value for the subgrade modulus, E_m, an in situ "weighted average," to be used for the calculation of subgrade parameters by the Odemark method.

DISCUSSION ON SURFACE AND SUBGRADE MODULUS PROFILES, E_x and E_{mz}

As shown in Figures 1 through 6, the surface modulus profile at and around the load position has large values caused by the stiffening effect of the structural layers [asphalt concrete (AC), base, and/or subbase]. For pavements that are whole and in good condition, the minimum values of the effective modulus profile, E_{min}, are larger than the subgrade modulus, E_m, because of the residual stiffening effect of the structural layers. This keeps the overall stiffness at the minimum point above that of the subgrade, which is assumed to have the lowest modulus value of all layers.

It has been observed in pavements that are cracked or broken that the minimum value of the effective modulus profile decreases. When the pavement is very severely cracked and completely broken, this minimum must finally approach a value that represents the subgrade modulus, i.e., the modulus near the top of the subgrade at and around the test load. This is illustrated in Figure 8 where the point (X_{min}, E_{min}) has moved very close to the subgrade modulus curve.

Equation 5 is used by the current PROBE program to calculate the effective modulus of subgrade deflection, and it

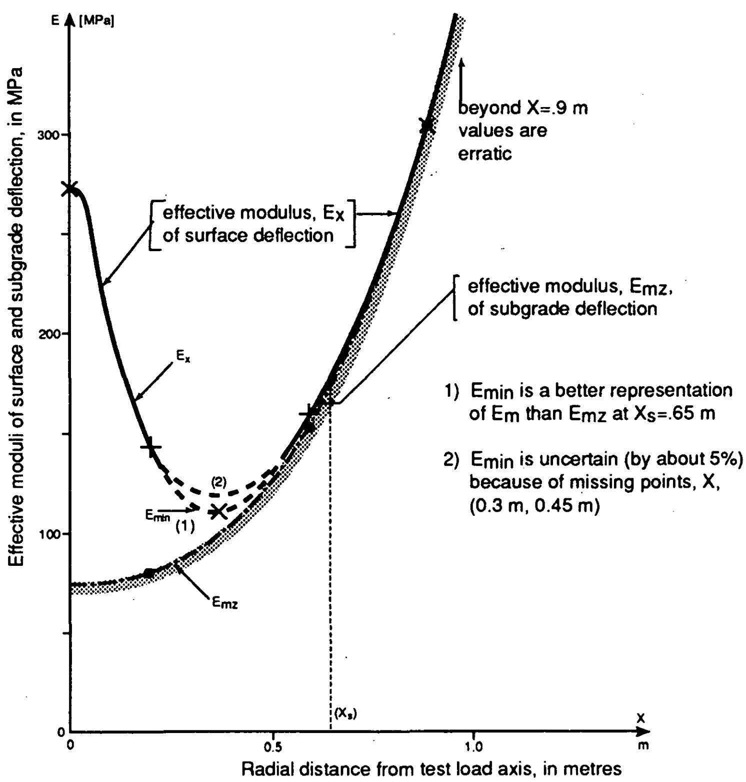

FIGURE 8 Effective modulus of surface and subgrade deflection of a "bad" data example, File S430-0.

must do so within the process of iteration of the backcalculation procedure. At each step of iteration, there is a slight change in E_m and H_{em}, until the deflections under the test load match. The subgrade modulus profiles in Figures 8 and 9 were calculated in this way.

The old PROBE version used the tail modulus function to estimate E_m at a selected distance, $X_t = 0.75$ m. This value was found by establishing consistency between the 1987 fall FWD tests, on neighboring points of Sections A and B on Highway 7N, stipulating that the subgrade modulus must be equal in both sections, except for statistical scattering. The sections were unequal in strength.

The new PROBE version also uses the tail modulus function. A similar calibration procedure leads to a smaller selected radial distance of about $X_s = 0.66$ m, because the procedure is now more complex.

Several "candidates" of the average in situ value of subgrade modulus E_m are compared:

1. The minimum value of the surface modulus profile, E_x, found by Lagrange interpolation (smallest value selected for broken pavements),
2. The value at $X_s = 0.66$ m of the tail modulus function, E_{mz} (often smallest value selected for whole pavements),
3. The value at $X_s = 0.72$ m of the subgrade modulus profile, E_{mz} (sometimes smallest value for pavements in fair condition), and
4. The average of the subgrade modulus profile up to $X = 1$ m, times a calibration factor (often smallest value for pavements in fair condition).

Figure 9 shows two examples of unbroken, whole AC pavements from a strong and weak design section of Highway 7N. Note that, in spite of the various E_x profiles, the subgrade modulus profiles E_{mz} converge near the test load.

NUMERICAL INDICATORS OF QUALITY AND STRENGTH

Further, the new PROBE program provides two indicators of relative strength or stiffness, in relation to the existing strength or stiffness of the soil. One of them, structural strength index (SSI), is based on the computed values of the surface modulus values only, before and independent of any computation or decision on the subgrade modulus. The other, structural integrity index (SII), uses the estimated subgrade modulus E_m. Both are based on the (approximate) area (A_x) under the surface modulus profile (E_x), from the load axis to X_s, or to the minimum value (E_{min}) at $X = X_{min}$. The two

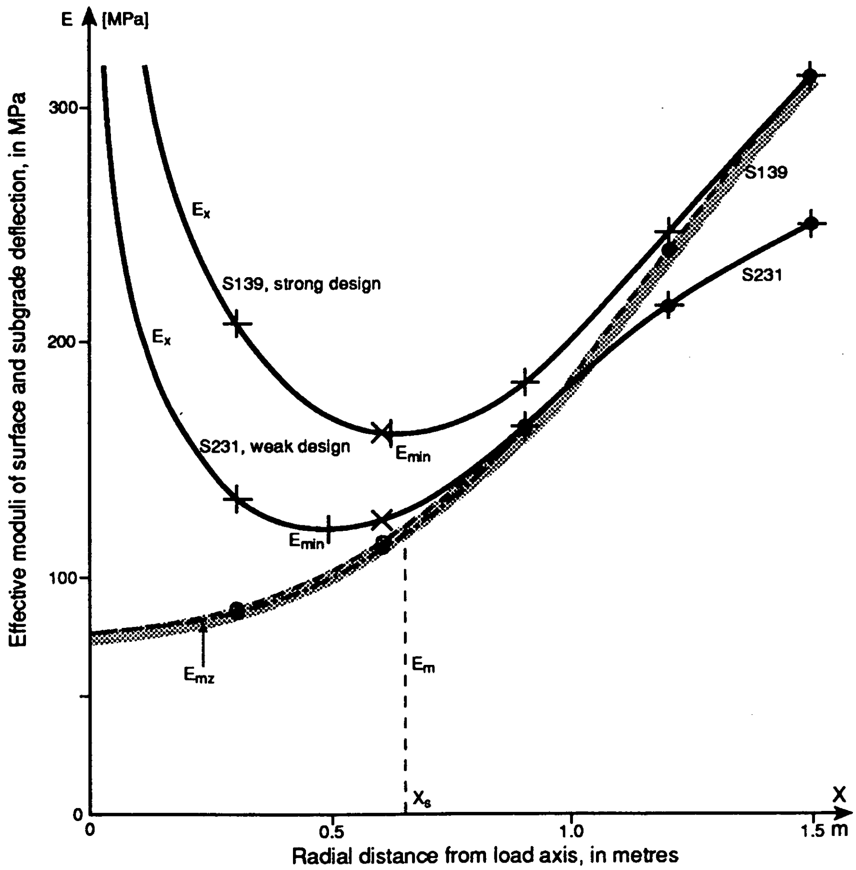

FIGURE 9 Convergence of effective modulus of subgrade deflection near the test load of strong (S139) and weaker section (S231) of Highway 7N test section.

indexes are

1. $SSI = A_x/(X_{min} \cdot E_{min})$ and
2. $SII = A_x/(X_s \cdot E_m)$

The index, SSI, can identify structurally weak or broken pavements that have values of SSI equal to or smaller than 1.5 (according to present experience).

The index, SII, is the more potent of the two. It measures the relative strength, stiffness, or integrity of the upper structural layers relative to the strength or stiffness of the subgrade. It is much affected by cracks at and near the load position, especially when the cracks run transversely to the direction of the FWD measurement. According to present experience, values can range from slightly below one (for severely cracked conditions) to above two (for pavements in good condition). SII is also subject to a small temperature adjustment with regard to a chosen standard temperature (such as 21°C). The SII is recommended to monitor flexible pavements for rehabilitation planning and overlay design, and valuable information can be obtained by chain-plotting SII along the whole pavement section. Note that SSI and SII quantify only a relative stiffness or strength under the load.

UNDERSTANDING FIELD DATA: COMPUTER SIMULATIONS

The increase of the effective modulus profile at distances from the load beyond the minimum value is concordant with the exponent, η, being larger than one, observed on all flexible pavements tested. Even values of η larger than two were measured on the major test section, Highway 7N, Toronto bypass. Observing and even trying to account for the fact does not mean that one fully understands it (*3*, *4*); therefore, computer simulations are helpful.

As indicated previously, a comparison of effective modulus profiles, using data from computer-generated and measured deflection bowls, clearly indicates that differences exist between actual field conditions and what is assumed for modeling. To investigate possible reasons for the observed differences, an idealized two-layer pavement was studied, taking into account the effects of bedrock location and impact loading, respectively. The problem case consisted of a 150-mm-thick plate with an elastic modulus of 2,250 MPa and a Poisson's ratio of 0.35, supported by a homogeneous subgrade with a modulus of 45 MPa and a Poisson's ratio of 0.50.

The deflection bowls were generated using the Bessel Fourier Series approach, described previously (*6*,*7*), assuming a peak load uniformly distributed over a 15-cm radius base plate. For the dynamic analysis, the impact load was applied as a half sine wave over an interval of 25 multisec, and a unit weight of 20 kN/m^3 was assumed.

Figure 10 provides a comparison of effective modulus profiles that were calculated using the generated deflection data, for various depths (D) of subgrade. As expected, the effective modulus for the elastostatic case, in which the subgrade extends to infinity ($D \rightarrow \infty$), approaches 45 MPa as the radial distance from the load get larger.

The dip below 45 MPa and the subsequent small gradual increase in effective modulus is caused by Poisson's ratio of the plate, which is different from that of the subgrade. For the elastodynamic case ($D \rightarrow \infty$), the effective modulus continuously decreases. This is not surprising, since the decay rate of surface wave amplitude for the semi-infinite half-space problem is known to be less than that of an elastotatic deflection bowl.

Figure 10 suggests that the increase in the effective modulus, observed when using real data, possibly can be attributed to the presence of bedrock. The strength of the increase of the effective modulus, with depth, depends on the subgrade thickness D. As D decreases, both the minimum effective modulus and the distant effective modulus increase. In the simulations, the distance at which the modulus is a minimum is approximately equal to the effective thickness of the pavement structure, i.e., $H_{em} \cong H_1\sqrt[3]{E_1/E_m}$.

The evidence from the analysis of the real and idealized deflection bowls indicates that the interpretation of the effective modulus profiles provides hints with respect to the deviation of assumed and actual behavior. This can be used

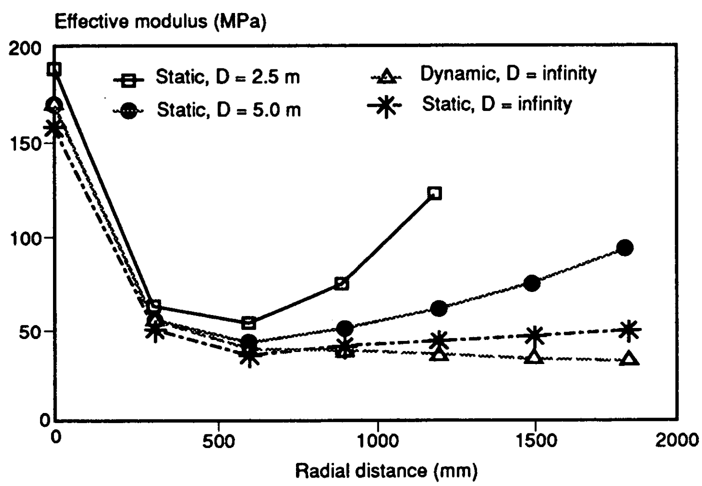

FIGURE 10 Dynamic and elastostatic computer simulation.

to evaluate the possible presence of unexpected features with respect to material properties or dimensions, or both, such as the presence of a bedrock face or harder layers of subgrade in its lower strata.

The presence of bedrock, at a finite distance below the pavement, represents a sudden change in the subgrade stiffness with depth. The increases in the effective modulus at larger radial distances from the load, observed in the field, can also be explained by a more gradual increase in the subgrade modulus with depth, which is almost certain to occur.

The surface deflections at larger distances from the load, used for the effective modulus calculations, are more sensitive to modulus increases with depth than those close to the load. Close to the load, the observed deflections are largely caused by the subgrade deformations in the upper zone of the subgrade, whereas the surface deflections farther away are caused by straining the deeper strata within the subgrade.

On the basis of the results from the two-layer problem, it appears that the effective modulus profile provides considerable information for characterizing a pavement structure, such as an estimate of subgrade modulus close to the load (close to E_{min} in broken pavements, smaller than E_{min} in whole pavements), strength of subgrade modulus increase with depth as indicated by $\eta - 1$, and stiffness of the upper pavement layer structure are reflected by H_{em}.

The results suggest that the effect of the subgrade modulus increase, with depth on the effective modulus profile, is more important than the influence associated with the dynamic nature of FWD loading. Most recently, however, Der-Wen et al. (*8*) have demonstrated that dynamic effects cannot be neglected when bedrock is close to the surface, i.e., within 2 to 5 m. Fortunately, often these effects are small and should not prevent an analytical solution, provided that deflections in the vicinity of the load are used for backcalculation analysis, i.e., not those much beyond a radius of H_{em}.

It is clear that the use of distant sensor readings can lead to considerable nonconservative errors in the subgrade modulus prediction, if the increases in subgrade stiffness with depth or the presence of bedrock, or both, are not properly taken into account. Other possible reasons for the positive

Standard test load, in kN:	40.034	Radius, in mm: 150
Standard contact pressure, in kPa:	566.4	
Layer thicknesses, in mm:	140, 169, 513	
Total:	Z = 822 mm	
Temperatures, at test (and standard), in degrees Celsius:	8 (21)	
Preliminary estimate of subgrade modulus:.	E = 129.39 MPa (at X = .66 m)	
η from regression analysis:	2.0818	
Average absolute % error of fit:	0.46	
Number of tail-sensors dropped in curve-fitting:	0	
Correlation coefficient:	.9998507	4 sensors, first at I = 4
Maximum effective modulus, in MPa:	604.91	
Minimum effective modulus, in MPa:	160.01, at a distance of X = 0.64 m	
Structural Strength Index:	1.927	

	Temperature	
Primary Response parameters:	**Unadjusted**	**Adjusted**
Structural Integrity Index:	2.31	2.00
Total deflection, in mm:	0.2465	0.3031
Radius of AC curvature, in m:	579.7	471.4
AC tensile micro-strain:	120.8	148.5
Subgrade deflection, in mm:	0.1259	0.1378
Subgrade stress, in kPa:	15.97	19.18
Subgrade micro-strain:	123.4	148.3

Equivalent thickness, H_{em}, in m:	1.263			
Subgrade modulus:	129.39 MPa			
Subgrade modulus candidates:	160.01	129.39	134.59	135.43
Layer moduli, in MPa:	7539.1	3486.2	260.3	129.4
Layer moduli are:	AC-mod	adjusted AC-mod	base & subbase	subgrade

Sensor	Distance, mm	Deflection, mm	Hyperbola, mm	Error of Fit, %	Effective Moduli MPa	
1	0	0.24647	0.00000	0.00	604.91	0.00
2	300	0.18657	0.67598	262.32	206.52	86.56
3	600	0.11638	0.15968	37.21	160.54	116.41
4	900	0.06838	0.06866	0.41	181.71	161.85
5	1200	0.03792	0.03772	-0.52	245.75	238.71
6	1500	0.02380	0.02371	-0.40	313.22	315.68
7	1800	0.01614	0.01622	0.51	385.00	393.78

FIGURE 11 Output file of PROBE-A run, File A:S139; example of good data, whole pavement.

subgrade modulus gradient at distant radii, not studied by the computer simulation, is the pressure dependence and anisotropy of granular, or AC materials, as they are composed of bonded or unbonded discrete particles (*2*).

NEW PROBE PROGRAM

As before, the program processes FWD deflection data from a sequential input file. The file contains geometrical information, such as radius of load distribution, layer thicknesses, and distances of sensors from the load axis. Further, for any number of target load levels (usually four), the file must provide the readings of pressures of the load cell and the deflections at each of the transducers or geophones, usually seven or more. The file contains also the mean temperature of the bitumen-bound layers, a normal temperature, and a standard load level chosen by the user.

The deflections, pressures, and loads from each target load level (in the quasi-elastic range) are already processed within the file creation program to one normal or standard load level (usually 9,000 lb or 40.034 kN) by adding the values and multiplying them by a factor. The PROBE program processes only values pertaining to the chosen normal load level.

Two examples of PROBE results are presented in the form of printed output in Figures 11 and 12. One is from a pavement of normal Ontario design (File S139), and the other is from a deteriorated section scheduled to be rehabilitated by an overlay (File S430), Section D on Highway 7N, 1990 data. Figures 11 and 12 correspond to the graphical representations in Figures 9 and 8, respectively.

The tables list all relevant information from one test location, and items can be chain plotted for a string of test locations along a section. In particular, the tensile strain and curvature under the load are computed in accordance with a method presented in 1988 (*9*). The subgrade parameters were computed by Odemark's method of equivalent layer thickness.

Vertical subgrade stresses and strains are modified by applying Froehlich's concentration factor, ranging from 3 to 4. The factor can be conceived as a function of the parameter, η, ranging from one to above two. This results in stresses and

Standard test load, in kN:	40.034	Radius, in mm: 150
Standard contact pressure, in kPa:	566.4	
Layer thicknesses, in mm:	90, 172, 340	
Total:	Z = 602 mm	
Temperatures, at test (and standard), in degrees Celsius:	26 (21)	
Preliminary estimate of subgrade modulus	E = 192.14 MPa (at X = .66 m)	
η from regression analysis:	3.4232	
Average absolute % error of fit:	14.37	
Number of tail-sensors dropped in curve-fitting:	1	
Correlation coefficient:	.9818988	4 sensors, first at I = 3
Maximum effective modulus, in MPa:	272.26	
Minimum effective modulus, in MPa:	111.35, at a distance of X = .37 m	
Structural Strength Index:	1.482	

	Temperature	
Primary Response parameters:	**Unadjusted**	**Adjusted**
Structural Integrity Index:	0.83	0.86
Total deflection, in mm:	0.5476	0.5182
Radius of AC curvature, in m:	133.7	141.3
AC tensile micro-strain:	336.7	318.6
Subgrade deflection, in mm:	0.2150	0.2123
Subgrade stress, in kPa:	46.61	44.10
Subgrade micro-strain:	418.6	396.0

Equivalent thickness,Hem, in m:	0.739			
Subgrade modulus:	111.35 MPa			
Subgrade modulus candidates:	111.35	192.14	226.90	228.10
Layer moduli, in MPa:	798.3	1161.5	225.8	111.3
Layer moduli are:	AC-mod	adjusted AC-mod	base & subbase	subgrade

Sensor	Distance, mm	Deflection, mm	Hyperbola, mm	Error of Fit, %	Effective Moduli MPa	
1	0	0.54763	0.00000	0.00	272.26	0.00
2	200	0.41101	5.25226	1177.87	143.57	74.06
3	600	0.11710	0.12220	4.35	159.55	150.54
4	900	0.03669	0.03050	-16.88	338.63	341.42
5	1200	0.00898	0.01139	26.89	1037.98	1060.03
6	1500	0.00585	0.00531	-9.36	1273.25	1300.52
7	1800	0.00859	0.00284	-66.89	723.44	736.95

FIGURE 12 Output file of PROBE-A run, File A:S430-o; example of bad data, broken pavement.

strains often larger (up to 30 percent) than those computed by elastic layer programs such as ELSYM5.

Besides those mechanistic parameters, there is plenty of information about quality and strength presented to give an indication of structural integrity or deterioration.

The upper-layer moduli are no more than rough estimates; they are needed only for adjustments to normal temperature. Such adjustment is required for any comparison of tests carried out at various temperatures. This adjustment makes the FWD method useful and feasible in the design and monitoring of flexible pavements (compared with other methods with less distinct temperature adjustment).

Note that moduli are not material properties, but are model parameters of the pavement structure/subgrade system as measures (i.e., "perceived") by the FWD instrument at the surface. However, the values of these model parameters should be consistent with those of the average material properties under investigation.

CONCLUSIONS AND RECOMMENDATIONS

The need to analyze FWD deflection data on severely cracked and broken flexible pavements and the differences between the theoretical modeling of fast workhorse programs and observed field performance of materials have spurred the development of new concepts with regard to deflection analysis:

1. The function of the effective modulus of measured surface deflection or the surface modulus profile,
2. The tail modulus function, and
3. The profile of the effective modulus of subgrade deflection.

All of these are used to calculate representative values of subgrade moduli, valid at and around the test load, and to provide valuable information on structural strength and integrity.

A computer simulation on a two-layer system has revealed that the deviation of field behavior from elastostatic modeling is not so much caused by dynamic influences, but can be traced better to certain properties of layer materials. Some of these are the increase of subgrade stiffness with depth, the presence of an often unrecorded bedrock face, or the anisotropy or pressure dependence of bounded or unbounded granular materials, especially the discontinuity of these materials. The aforementioned effective modulus profiles can serve as a key to obtain information regarding these items. The new revised PROBE program is a first attempt to quantify such information. Research is being continued to provide a better understanding of the relationship between the effective modulus profile and in situ properties of materials and design features.

Deflections beyond the minimum of the effective modulus profile cannot be used directly to calculate a representative estimate of the subgrade modulus, only indirectly, via the tail modulus function (*3*,*4*).

If they are used directly, estimates of subgrade moduli may be excessively high. The subgrade modulus must be calculated from deflections closer to the load. The deflections beyond the minimum effective modulus, however, are used to provide information on the condition of the pavement structure.

Flexible pavements of usual design (bitumen-bound layers on granular bases) behave very differently from those designed with elastic continuum materials. Backcalculation of all layer moduli using distant deflections is futile. In the approach presented here, backcalculation is used only with regard to the deflection under the load and only to obtain an estimate of the subgrade modulus. Emphasis is given to interpretation, which is more useful than backcalculation for the practicing engineer.

REFERENCES

1. E. J. Yoder and M. W. Witczak. *Principles of Pavement Design*, 2nd ed., John Wiley and Sons, Inc., New York, N.Y.
2. P. Ullidtz. *Pavement Analysis*. Elsevier, Amsterdam, the Netherlands, 1987.
3. F. W. Jung. *Interpretation of Deflection Basin for Real-World Materials in Flexible Pavements*. Research Report RR-242. Ministry of Transport, Ontario, Canada, 1990.
4. F. W. Jung et al. Testing and Interpretation with the Falling Weight Deflectometer (FWD) in Ontario. Presented at 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 1991.
5. R. L. Lytton et al. *NCHRP Report 327*: Determining Asphaltic Concrete Pavement Structural Properties by Nondestructive Testing. TRB, National Research Council, Washington, D.C., June 1990.
6. D. Stolle, D. Hein, and Y. Wang. *Elastostatic Analysis and Backcalculation Estimates of Pavement Layer Moduli*. C39-C59. Roads and Transportation Association of Canada, 1988.
7. D. Stolle. Modelling of Dynamic Response of Pavements to Impact Loading. In *Computers and Geotechnics*, 1991, pp. 83–94.
8. Der-Wen et al. Effect of Depth to Bedrock on Deflection Basin Obtained with Dynaflect and FWD Tests. Presented at the 71st Annual Meeting of the Transportation Research Board, Washington, D.C., 1992.
9. F. W. Jung. Direct Calculation of Maximum Curvature and Strain in AC-Layers of Pavements from Load Deflection Basin Measurements. In *Transportation Research Record 1169*, TRB, National Research Council, Washington, D.C., 1988.