New Scenario for Backcalculation of Layer Moduli of Flexible Pavements

A. SAMY NOURELDIN

A new backcalculation scenario that uses falling weight deflectometer (FWD) deflection bowl data to directly backcalculate subgrade modulus and overall pavement modulus and predict effective structural number of the pavement is presented. The procedure allows for decomposing measured maximum deflection into two components: subgrade deflection and pavement deflection. Execution of the scenario accounts for conditions when thickness data are not available, not reliable, or not representative. The scenario depends on a concept that is not related to selection of seed values. The concept is that there is a unique location on the surface of the pavement at a radial distance r_x from the loading center that deflects with a value D_x exactly equal to the deflection of the point on the top of subgrade underneath the loading center. The scenario was field tested using FWD deflection measurements representing newly constructed roads, roads with considerable deterioration, top of compacted subgrade, top of subbase, top of base, and top of wearing surface. General observations on field applications and a field testing example are introduced.

Calculation of load-related pavement surface deflections at specific points, using material properties of pavement layers (modulus, Poisson's ratio, and thickness), is well established. Backcalculation of pavement layer moduli is a reversed procedure. Pavement layer moduli are calculated using load-related pavement surface deflection measurements (actual deflection bowl) and available thickness or coring data and making reasonable assumptions for Poisson's ratios.

The scenario of this backcalculation process usually takes the form of assuming acceptable values of pavement layer moduli (seed values), predicting a theoretical deflection bowl, comparing the theoretical deflection bowl with the actual deflection bowl, and accepting moduli values when the difference between the theoretical bowl and the actual bowl is not significant.

This technique has passed through many adjustments and modifications. Adjustments are usually made to avoid obtaining excessive modulus values for the pavement surface layer. Seed values are forced to be in certain ranges. A rigid base is sometimes assumed. Actual deflection measurements are sometimes adjusted for seasonal variations before the backcalculation procedure is conducted instead of investigating the effect of seasonal variations on the backcalculated moduli values.

Several questions are still to be answered. How can backcalculated data be used to compare between pavement sections? How can backcalculated data be used to identify deficient pavement layers? Is it possible to bypass the requirement of thickness data in the backcalculation procedure, especially when these data are not reliable and field coring is not representative?

This paper presents a new scenario for the backcalculation process. Seed values will not be required to predict a theoretical deflection bowl and compare it with the actual deflection bowl. Instead, an effective total thickness value is computed directly from the actual deflection bowl and is compared with the actual total thickness existing on the top of the subgrade. Computed moduli associated with the actual total thickness are the resulting backcalculated moduli. In addition, an alternative backcalculation process predicting the in situ effective total thickness is introduced for cases where thickness data are not available, not reliable, or not representative.

UNDP Ministry of Communications, Riyadh 11178, Saudi Arabia.

METHODOLOGY

Equipment and Loading Conditions

The scenario presented herein is based on two-layer elastic analysis and applicable to falling weight deflectometers (FWDs). The FWD used has a plate radius of 6.0 in. (15 cm) and seven geophones located at distances 0, r_1, r_2, r_3, r_4, r_5, and r_6 from the loading center. These geophones measure the deflections D_0, D_1, D_2, D_3, D_4, D_5, and D_6 at the surface of the flexible pavement due to a 9,000-lb load. If a different load is used, deflection measurements should be normalized to the load of 9,000 lb.

Concept

The concept of the procedure is that a unique location exists on the surface of the pavement at a radial distance r_x from the loading center that deflects with a value D_x exactly equal to the deflection of a point on the top of the subgrade underneath the loading center (Figure 1). If this unique location is found, the overall pavement modulus (E_p), the subgrade modulus (E_{SG}), the effective total thickness (T_x), the subgrade deflection underneath the loading center (D_x), and the pavement deflection underneath the loading center ($D_0 - D_x$) can be determined. The following section indicates how this unique location is found and how the backcalculation scenario is executed for two cases. The first case applies when pavement thickness data are available, and the second case applies when thickness data are not available.

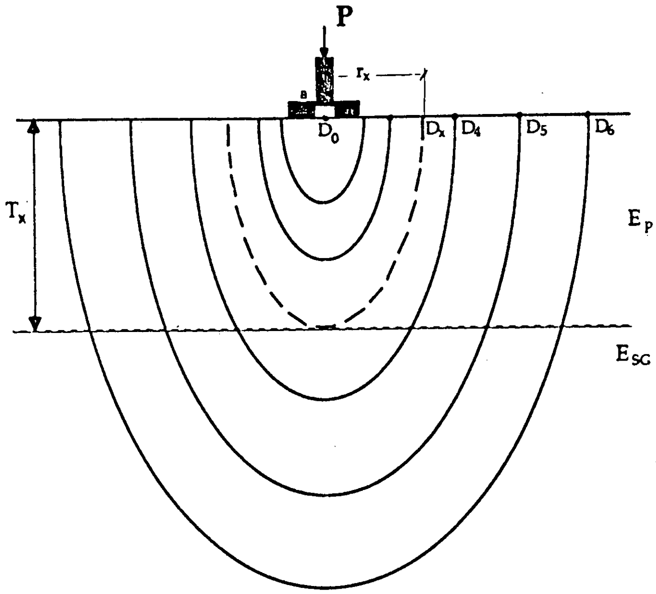

FIGURE 1 Contour lines of equal vertical deflections within the pavement system.

Execution of Backcalculation Scenario

Thickness Data Available

When thickness data are available and reliable through records or field coring, the unique location described above can be determined and the backcalculation scenario can be executed as follows:

1. The outer geophone location is assumed to be the unique location (i.e., $r_x = r_6$ and consequently $D_x = D_6$).
2. Determine subgrade modulus (E_{SG}) using r_6 and D_6 values for r_x and D_x using the following equation:

$$E_{SG} = \frac{2{,}149}{r_x D_x} \tag{1}$$

where D_6 and r_6 are in inches and E_{SG} is in psi. This equation is based on Boussinesq's deflection equation (*1*). This method of determining the subgrade modulus was proposed by Ullidtz (*2,3*) for deflections measured outside the loading plate. The method was also reported previously by Noureldin and Sharaf (*4*) and Hall et al. (*5*).

3. Determine the overall pavement modulus (E_p) using r_6 and D_6 for r_x and D_x values and using the following equation:

$$E_p = \frac{716 - \dfrac{2{,}149}{r_x}}{D_0 - D_x} \tag{2}$$

where E_p is in psi and D_0, D_6, and r_6 are in inches. This equation is based on Burmister's method of deflection in two-layer systems (*6*). The equation was reported by Noureldin and Sharaf (*4*).

4. Determine the effective total thickness, T_x, using r_6 and D_6 for r_x and D_x and using the following equation:

$$T_x = \left[\frac{D_0 - D_x}{D_x \left(\dfrac{r_x}{3} - 1 \right)} \right]^{1/3} * (4r_x^2 - 36)^{1/2} \tag{3}$$

where D_0, D_6, r_6, and T_x are in inches.

This equation is also based on the Burmister and Odemark method of deflection in a two-layer system (*6,7*) and the concept of equivalent thicknesses described by Barber (*8*). The equation was reported by Noureldin and Sharaf (*4*).

5. Repeat Steps 1 through 4 for each geophone outside the loading plate.
6. Draw the relationships r_x versus T_x, r_x versus E_{SG}, and r_x versus E_p, where the horizontal axis coordinates are for r_x equal to r_1, r_2, r_3, r_4, r_5, and r_6 (Figure 2).
7. The backcalculated subgrade modulus and the overall pavement modulus are those associated with the unique location at the radial distance r_x (Figure 2).
8. Subgrade deflection underneath the center of the loading plate is the deflection of the unique location (D_x). Pavement deflection is the difference between the maximum deflection and the deflection of the unique location ($D_0 - D_x$).

Table 1 presents a sample of deflection measurements obtained by the FWD on a 16-in. flexible pavement. Table 2

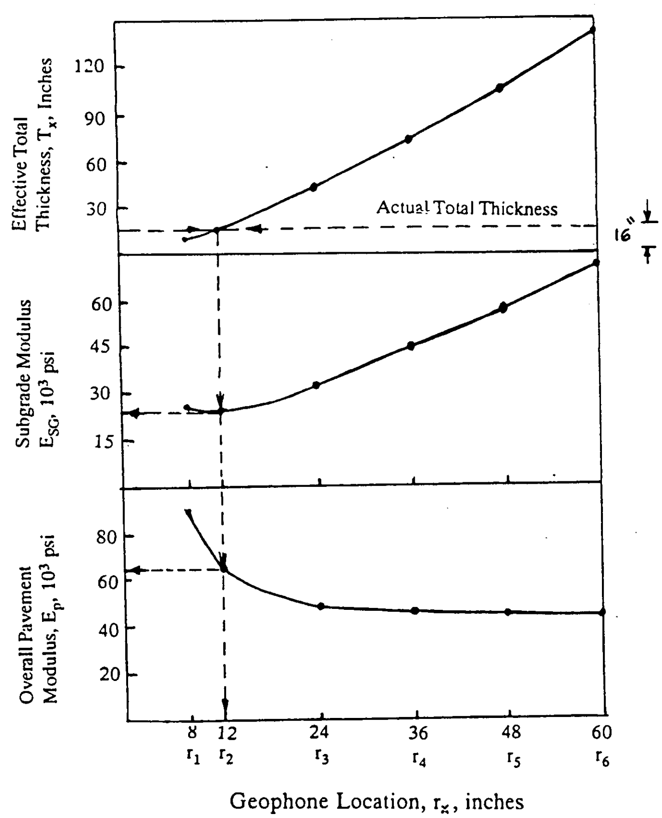

FIGURE 2 Determination of unique location.

TABLE 1 FWD Deflection Measurements on a 16-in. Flexible Pavement (Load = 9,000 lb; Plate Radius = 6.0 in.)

Location	0	1	2	3	4	5	6
Radius, r_x , inches	0	8	12	24	36	48	60
Deflection, D_x , mils	D_0	D_1	D_2	D_3	D_4	D_5	D_6
	15.9	10.9	7.6	2.8	1.3	0.8	0.5

TABLE 2 Subgrade Modulus (E_{SG}), Overall Pavement Modulus (E_p), and Effective Total Thickness (T_x) Computation Steps

		E_{SG} (psi)	E_p (psi)	T_x (inches)
rx = r6 = 60 in	Dx = r6 = 0.5 mils	71,600	44,200	140.8
rx = r5 = 48 in	Dx = r5 = 0.8 mils	56,000	44,500	103.4
rx = r4 = 36 in	Dx = r4 = 1.3 mils	45,900	45,000	72.3
rx = r3 = 24 in	Dx = r3 = 2.8 mils	32,900	47,800	41.6
rx = r2 = 12 in	Dx = r2 = 7.6 mils	23,600	64,700	16.6
rx = r1 = 8 in	Dx = r1 = 10.9 mils	24,700	89,500	9.6

gives the computation steps for determining subgrade modulus (E_{SG}), overall pavement modulus, and effective total thickness (T_x). In addition Figure 2 shows r_x versus T_x, r_x versus E_{SG}, and r_x versus E_p relationships. The unique location is at $r_x = r_2 = 12$ in., corresponding to an actual total thickness of 16 in. Subgrade modulus and overall pavement modulus are 23,000 psi and 65,000 psi, respectively (Figure 2). The subgrade deflection underneath the loading center is $7.6 * 10^{-3}$ in. (surface deflection at the unique location). The pavement deflection underneath the loading center is $8.3 * 10^{-3}$ in. ($15.9 * 10^{-3}$ in. $- 7.6 * 10^{-3}$ in.).

Thickness Data Not Available

When thickness data are not available through design records or field coring, a need exists for an alternative scenario for the backcalculation process. The need also exists when nondestructive deflection coverage is conducted at a network level (and not at a project or research level).

The total pavement thickness is defined as the sum of individual thicknesses of pavement layers above the subgrade layer. An alternative definition is that total pavement thickness is the vertical distance between the surface of the pavement and the top of the weakest pavement layer within the pavement system. As long as pavement layers are stiffer than the subgrade, the two definitions are equivalent. However, if the subbase, base, or surface layer is less stiff than the subgrade, the alternative definition yields an effective total thickness that is less than the actual total thickness. Conversely, if the top portion of the subgrade layer is compacted (or consolidated) more than deeper portions, the alternative definition yields an effective total thickness that is more than the actual total thickness.

Using the concept of effective total pavement thickness described above, the layer of lowest modulus can be searched, and the distance between the pavement surface and the top of this layer is considered the effective total pavement thickness. The alternative backcalculation scenario is, then, executed as follows:

1. Find the unique location of the geophone at a distance r_x from the center of the loading plate measuring a deflection D_x such that $r_x * D_x$ is maximum. This means that r_6D_6, r_5D_5, r_4D_4, r_3D_3, r_2D_2, and r_1D_1 values should be calculated, and the maximum value is to be selected. If r_4D_4 is the largest value, for example, $r_x = r_4$ and $D_x = D_4$.
2. Determine the subgrade modulus (E_{SG}), overall pavement modulus (E_p), and effective total thickness (T_x) using Equations 1, 2, and 3.
3. The subgrade deflection underneath the loading center is D_x, and the pavement deflection underneath the loading center is $(D_0 - D_x)$.

In the computation example previously introduced,

- $r_2 * D_2$ represents the largest $r_x * D_x$ multiplication value; hence $r_x = r_2 = 12$ in. and $D_x = D_2 = 7.6 * 10^{-3}$ in.;
- $E_{SG} = 23,000$ psi, $E_p = 65,000$ psi, and effective total thickness = 15.8 in.; and
- Subgrade deflection is $7.6 * 10^{-3}$ in. and pavement deflection is $8.3 * 10^{-3}$ in. ($15.9 * 10^{-3}$ in. $- 7.6 * 10^{-3}$ in.).

Assumptions and Limitations

The scenario has the following assumptions and limitations:

1. The pavement is an idealized elastic two-layer flexible system.
2. The material is weightless, homogeneous, and isotropic.
3. The pavement layer has a uniform thickness and an infinite width in all horizontal directions. The bottom layer (subgrade) has an infinite thickness.
4. Poisson's ratios of the two layers are equal to 0.5.
5. The top of subgrade is the top of the layer of lowest modulus in the pavement system (when thickness data are not available).
6. The total pavement thickness is considered to be the distance between the top of the pavement and the top of the layer of lowest modulus in the pavement system (when thickness data are not available).
7. Thin pavements that are less than the radius of the loading plate in thickness will yield inaccurate results.

Determination of AASHTO Effective Structural Number

The *AASHTO Guide for Design of Pavement Structures* (*9*) recommended a nondestructive deflection testing procedure for determination of the effective structural number, SN_{eff}. This procedure follows an assumption that the structural capacity of the pavement (represented by its structural number) is a function of its total thickness in inches (T_x) and overall modulus in psi, (E_p), such that

$$SN_{eff} = \sqrt[3]{\frac{E_p}{11 * 10^6}} * T_x \qquad (4)$$

Equation 4 was not explicitly introduced in the AASHTO guide and was originally reported by Noureldin and Al Dhalaan (*10*) and later by Hall et al. (*5*). The equation presented by Hall et al. (*5*) was

$$SN_{eff} = 0.0045\ D\ \sqrt[3]{E_p} \tag{5}$$

where D is the total pavement thickness and E_p is the effective modulus of the pavement. As can be easily noted, Equations 4 and 5 are practically the same.

After substituting Equations 2 and 3 into Equation 4 (or 5) to determine the effective structural number (SN_{eff}) as a function of r_x and D_x (radii and deflection associated with the unique location described in this paper), the SN_{eff} equation becomes

$$SN_{eff} = \frac{(4r_x^2 - 36)^{1/2}}{17.234(r_x * D_x)^{1/3}} \tag{6}$$

This equation can be easily executed as a part of the backcalculation scenario presented in this paper, whether or not thickness data are available. In addition, the simplicity of the equation allows its use at the research, project, or network level.

APPLICATION

General Observations

The availability of long roadway segments in Saudi Arabia that are still in the construction stages provided the opportunity to test the backcalculation scenario presented in this paper under real conditions. The FWD was used to obtain measurements on top of compacted subgrade, subbase, base, and wearing surface layers for the same locations on a number of roadway segments. The following observations were obtained:

1. Maximum deflection (D_0) decreased after the construction of any layer.
2. Effective structural number (SN_{eff}) and effective total thickness (T_x) estimated by the backcalculation process presented in this paper increased after the construction of any layer.
3. The unique location defined in this paper got away from the loading center (r_x increased) after the construction of any layer.
4. The backcalculated subgrade modulus (E_{SG}) remained practically the same after construction of each individual layer.
5. The backcalculated subgrade modulus was predicted by the first geophone outside the loading plate in all tests conducted on top of subgrade.
6. The computation of subgrade modulus, using the measurement of maximum deflection (D_0) and assuming one-layer analysis, always resulted in a value larger than that predicted by other geophones. This was true even when the deflection measurements were taken on top of the compacted subgrade.

Effect of Seasonal Variations

The backcalculation process presented in this paper was applied using nondestructive deflection measurements representing fall, winter, spring and summer conditions on specific roadway sections in Saudi Arabia. Although this research work is still in its early stages, preliminary results were obtained. The results suggest that under the dry conditions prevailing in Saudi Arabia, backcalculated subgrade modulus (E_{SG}) is slightly affected by changes in air temperature, whereas backcalculated pavement modulus (E_p) is significantly affected. In addition the estimated effective total thickness (T_x) remained the same during the four seasons and was practically equal to the actual total pavement thickness. However, the estimated effective structural number (SN_{eff}) was shown to drop considerably during the hot conditions of summer.

Demonstrative Field Testing Example

Table 3 presents FWD measurements on a 1,300-ft roadway segment. Deflection measurements were taken at a lateral distance of 3 ft from the pavement edge each 100 ft. The roadway segment exhibited low to medium severity, wheelpath longitudinal cracking, and frequent transverse cracking. The pavement cross section consists of 6-in. full-depth asphalt on top of a 10-in. subbase layer (i.e., total pavement thickness is 16 in.). The design structural number was originally 3.74.

The backcalculation scenario presented previously was executed assuming that thickness data were not available.

Table 4 gives the backcalculated modulus values, effective total thickness, and effective structural number (SN_{eff}) along

TABLE 3 FWD Data on 1,300-ft Segment (Load = 9,000 lb; Plate Radius = 6.0 in.)

Location	0	1	2	3	4	5	6	Temperature	
Radius (in.)	0	8	12	24	36	48	60		
Dist. Feet	D_0 mils	D_1 mils	D_2 mils	D_3 mils	D_4 mils	D_5 mils	D_6 mils	Air °F	Pave °F
0	13.1	9.1	6.4	2.6	1.2	0.6	0.4	93	97
100	14.1	10.1	7.3	2.8	1.3	0.8	0.5	93	100
200	15.9	10.9	7.6	2.6	1.1	0.7	0.5	94	100
300	10.3	7.9	6.0	2.8	1.6	1.0	0.6	92	100
400	12.8	8.9	6.3	2.5	1.2	0.7	0.4	92	99
500	12.2	7.6	5.1	1.5	0.5	0.3	0.1	93	99
600	11.1	8.3	6.3	2.7	1.3	0.8	0.5	93	100
700	12.1	8.1	5.6	1.9	0.8	0.4	0.2	91	96
800	15.6	10.6	7.3	2.8	1.4	0.9	0.5	91	98
900	11.3	7.5	5.1	2.2	1.3	0.8	0.5	91	96
1000	13.0	9.4	6.9	2.5	1.0	0.5	0.2	91	98
1100	8.5	6.2	4.8	2.3	1.2	0.8	0.5	91	96
1200	14.1	10.1	7.4	3.0	1.5	1.0	0.6	91	97
1300	13.6	9.1	6.4	2.4	1.2	0.7	0.5	91	96

Deflections are in mils (1/1000 inch)

TABLE 4 Backcalculated Moduli, Effective Total Thickness, and Effective Structural Number

Distance Feet	Subgrade Modulus E_{SG} psi	Overall Pavement Modulus E_P, psi	Effective Total Thickness T_x, inches	Effective Structural Number SN_{eff}
0	28,000	80,100	16.36	3.17
100	24,500	79,000	15.74	3.04
200	23,600	64,700	16.59	3.00
300	29,800	124,900	14.42	3.24
400	28,400	82,600	16.28	3.19
500	35,100	75,600	17.99	3.42
600	28,400	111,900	14.72	3.19
700	32,000	82,600	16.93	3.32
800	24,500	64,700	16.82	3.04
900	35,100	86,600	17.20	3.42
1000	26,000	88,000	15.46	3.09
1100	37,300	145,100	14.77	3.49
1200	24,200	80,100	15.59	3.02
1300	28,000	74,600	16.76	3.17
Mean	28,900	88,600	16.12	3.20
Std. Dev.	4,400	23,000	1.04	0.16
Coeff. of Var.	15.20%	26%	6.45%	5.00%

the roadway segment. The variability in overall pavement modulus values, as represented by the coefficient of variation, was more than the variability in the subgrade modulus, possibly because of cracking observed on the pavement surface. Computed effective total thickness was practically equal to the actual total thickness (16.0 in.) and exhibited relatively low variability. The mean value of the effective structural number (SN_{eff}) was lower than the design value (3.74). However, the SN_{eff} values had shown the lowest variability.

Figures 3, 4, and 5 show moduli, effective total thickness, and effective structural number profiles along the 1,300-ft roadway segment.

Table 5 presents the maximum deflection, subgrade deflection, and pavement deflection values underneath the center of the FWD loading plate along the roadway segment. Figure 6 shows the profiles of these deflection values. The

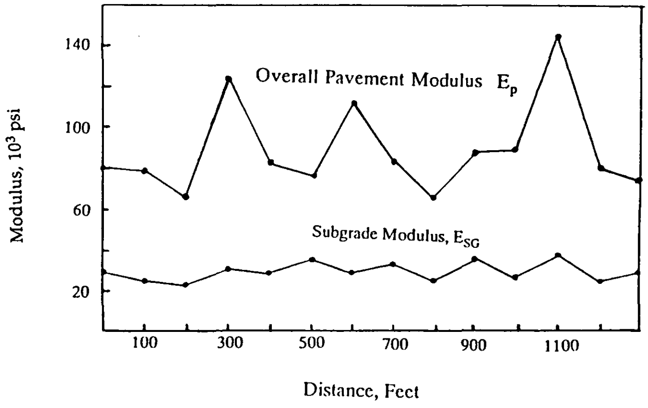

FIGURE 3 Backcalculated moduli values.

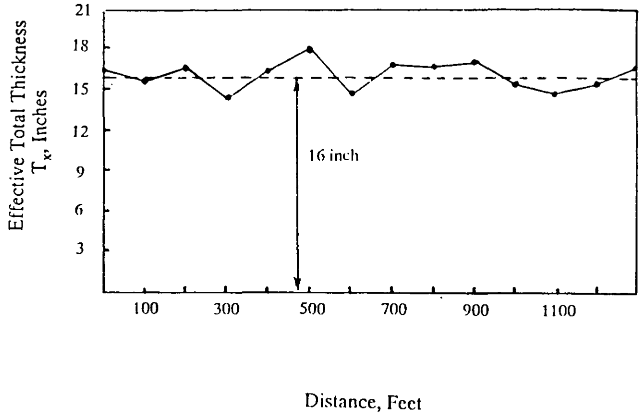

FIGURE 4 Effective total thickness.

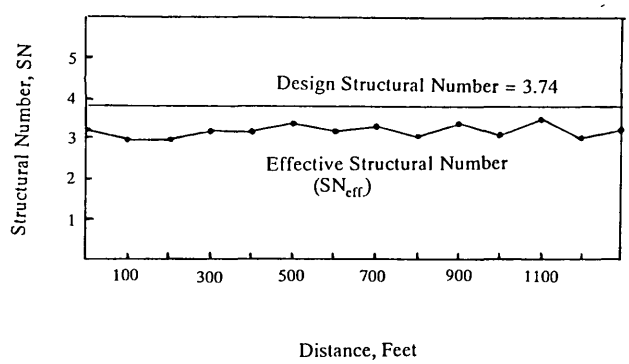

FIGURE 5 Effective structural number (SN_{eff}).

TABLE 5 Deflection Values Underneath the Center of the FWD Loading Plate

Distance Feet	Maximum Deflection D_o, mils	Subgrade Deflection D_x, mils	Pavement Deflection $(D_o - D_x)$, mils
0	13.1	6.4	6.7
100	14.1	7.3	6.8
200	15.9	7.6	8.3
300	10.3	6.0	4.3
400	12.8	6.3	6.5
500	12.2	5.1	7.1
600	11.1	6.3	4.8
700	12.1	5.6	6.5
800	15.6	7.3	8.3
900	11.3	5.1	6.2
1000	13.0	6.9	6.1
1100	8.5	4.8	3.7
1200	14.1	7.4	6.7
1300	13.6	6.4	7.2
Mean	12.7	6.32	6.37
Std. Dev.	2.0	0.92	1.33
Coeff. of Var.	15.80%	14.50%	20.90%

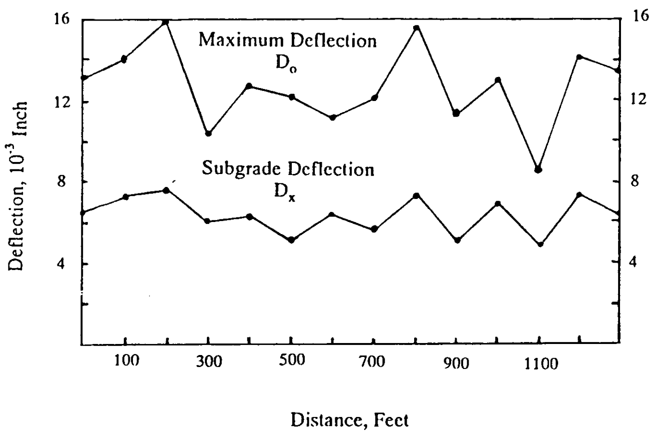

FIGURE 6 Deflection profiles underneath the center of the FWD loading plate.

variability in pavement deflection was higher than the variability in subgrade deflection (Table 5 and Figure 6). This also might be attributed to the observed cracks on the pavement surface.

SUMMARY

A new scenario for backcalculation of layer moduli of flexible pavements was introduced. It allows for the determination of subgrade modulus, overall pavement modulus, and effective structural number. In addition, it enables decomposition of measured maximum deflections into two components: subgrade deflection and pavement deflection. The scenario can be executed whether or not thickness data are available. Necessary computations are directly made using deflection bowl data on a seven-geophone FWD. The new scenario is suggested as a simple, quick, and reliable backcalculation approach for evaluation of flexible pavements.

REFERENCES

1. J. Bousinesq. *Application des Potentials à l'Étude de l'Equilibre et du Mouvement des Solides Elastiques*. Gauthier-Villars, Paris, 1885.
2. P. Ullidtz. *Pavement Analysis*. Elsevier Science Publishers B. V., 1987.
3. P. Ullidtz. Overlay and Stage by Stage Design. *Proc. Fourth International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., 1977.
4. A. S. Noureldin and E. A. Sharaf. A Simplified Mechanistic Algorithm for Pavement Analysis. Presented at 71st Annual Meeting of Transportation Research Board, Washington, D.C., 1992.
5. K. T. Hall, M. I. Darter, and R. P. Elliot. Revision of AASHTO Pavement Overlay Design Procedures. Presented at 71st Annual Meeting of Transportation Research Board, Washington, D.C., 1992.
6. D. M. Burmister. The Theory of Stresses and Displacements in Layered Systems and Application to the Design of Airport Runways. *HRB Proc.*, 1943.
7. N. Odemark. *Investigations as to the Elastic Properties of Soils and Design of Pavements According to the Theory of Elasticity*. Meddelande 77, Statens Vägenstitut, Stockholm, Sweden, 1949.
8. E. S. Barber. Discussion. *HRB Proc.*, Vol. 20, 1940.
9. *AASHTO Guide for Design of Pavement Structures*. Vol. 2. American Association of State Highway and Transportation Officials, Washington, D.C., 1986.
10. A. S. Noureldin and M. A. Al Dhalaan. Establishment of Some Structural Parameters to Pavement Evaluation Using the Falling Weight Deflectometer. Presented at 70th Annual Meeting of the Transportation Research Board, Washington, D.C., 1991.

The contents of this paper reflect the views of the author, who is solely responsible for the facts and the accuracy of the contents presented herein. The contents do not necessarily reflect official views or policies of the Saudi Arabian Ministry of Communications. This paper does not constitute a standard, specification, or regulation.