

Title of the Paper:

FWD Data Analysis without Layer Thickness Information

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FWD Data Analysis without Thickness Information

ABSTRACT

New York State Department of Transportation (NYSDOT) has developed a new method for estimating the number of layers and the modulus of each layer below the pavement surface, directly from non-destructive deflection testing. Current deflection analysis use backcalculation software programs to determine pavement moduli. Contrary to these software programs, the NYSDOT method based on the Hossain-Boussinesq equations does not require layer thickness information. The Hossain-Boussinesq equations are modified Boussinesq equations which determine the surface and sub-layer moduli for a pavement system. This method develops several parameters and influence factors which are used to calculate layer moduli and layer thickness from the surface modulus and apparent sublayer moduli.

This method also identifies the existence of a bound layer (for example, PCC or asphalt/cement treated base) between the surface layer and the base/subbase, and a stiff layer below the subgrade. If a bound layer exists, the method estimates its modulus and thickness. If a stiff layer is present below the subgrade, the method first determines the location of subgrade and the subgrade modulus. The location of stiff layer is determined next. The method then corrects the deflections to determine layer modulus and thickness for the remaining layers.

Several examples and case studies are presented here to show the applicability and usefulness of this new method. The method using Hossain-Boussinesq equations, equips the user with a better understanding of the structural conditions of the underlying pavement layers. Most importantly, all computations are performed with a user-friendly spreadsheet program which guides the user with straight forward input.

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INTRODUCTION

Nondestructive testing on pavements continues to have a significant impact on the design and evaluation of pavement systems. To determine the layer moduli of a pavement system, deflection measurements from nondestructive testing (NDT) have been commonly performed.

The deflection basin measurements are commonly made by an impact loading device such as Falling Weight Deflectometer (FWD). Although the FWD data collection method is quick, the data analyses techniques may require longer time. At present, most highway agencies are using the backcalculation method for pavement evaluation. The available programs for the backcalculation of layer moduli require seed moduli and layer thicknesses as input, and therefore, may introduce user bias. The layer thicknesses are obtained through coring and drilling may be time consuming in performing data analysis. Although these backcalculation programs yield layer moduli quickly, these values may differ from one program to the next depending on the program tolerance limits and seed moduli. Considerable background information on this method is provided in the existing studies [1-4].

The GPR (Ground Penetrating Radar) is used to determine pavement layer thicknesses fairly quickly. Efforts are underway to combine the FWD with the GPR device. Although this will improve the data analysis technique, the accompanying increase in cost will be significant.

However, a different approach may be proposed for pavement evaluation using the deflection data without any prior information of the pavement. Based on a direct or forward calculation method, this approach would determine the following:

1. Presence of stiff layer beneath the subgrade,
2. Correct the deflections due to stiff layer,
3. Location of subgrade and its modulus,
4. Location of the stiff layer and its modulus (if needed), and
5. Modulus and approximate thickness of each layer above the subgrade.

To date, no other method determines the above properties from the deflection and the load data only. This paper presents a new method developed based on the Hossain-Boussinesq equations to determine the above pavement properties. The required relationships are developed to identify and determine each property.

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DESCRIPTION OF METHODOLOGY

Modified Boussinesq Equations

A brief description of this methodology is presented here. The Boussinesq equation for a flexible plate with radius, a and a uniform pressure, $q(0)$ placed on surface of a subgrade (semi-infinite medium also known as half-space) is given by the following equation:

$$E_s(0) = 2(1-\mu^2) a q(0) / d(0) \quad (1)$$

Where: $E_s(0)$ = Surface modulus at the load center,
 $q(0)$ = Pressure at the load center,
 $d(0)$ = Deflection at the load center
 a = Plate radius, and
 μ = Poisson's Ratio.

Since modulus is constant in a subgrade, the Equation 1 can be generalized as

$$E_s(r) = 2(1-\mu^2) a q(r) / d(r) \quad (2)$$

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Where, $q(r)$ = Pressure at a distance r from the load center,
 $d(r)$ = Deflection at the location r

Since $E_s(0) = E_s(r)$ for a subgrade, we get from Equations 1 and 2

$$q(0) / q(r) = d(0) / d(r) = f(r), \quad (3)$$

$$q(r) = q(0) / f(r) \quad (3a)$$

Where, $f(r)$ is a pressure-decreasing factor.

The pressure-decreasing factor, $f(r)$ increases as r increases. This is because the pressure decreases as the distance from the load center increases. This decrease in pressure is due to the geometrical spreading and absorption of wave motion propagating through the medium. The experimental results indicate that the losses by spreading are more important than the losses by absorption when the motion is associated with low frequencies and short distances [5]. This indicates that $f(r)$ calculated based on a half-space is also valid for multi-layered pavement and geologic systems.

Substituting $q(r)$ from Equation 3a into Equation 2, we get

$$E_s(r) = 2(1-\mu^2) a q(0) / \{f(r) * d(r)\} \quad (4)$$

Using ELSYM5 [6] forward calculation program for a subgrade with modulus, $E = 10,000$ psi, $q(0) = 82$ psi and plate radius, $a = 5.91$ inches; the deflections and $f(r)$ values are calculated and are shown in Table 1.

Table 1 Deflections, $d(r)$ and Pressure Decreasing Factors, $f(r)$ for a Subgrade

Distance, r in.	Deflection mils	$f\{r\} = d(0)/d(r)$
0	81.42	1

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4	71.11	1.145
6	49.98	1.629
8	32.70	2.49
12	20.72	3.93
18	13.37	6.09
24	10.02	8.12
36	6.68	12.18
48	5.01	16.24
60	4.01	20.30
72	3.34	24.37

The pressure decreasing factor, $f(r) = 2r/a$ when $r \geq 2a$.

Again, the modulus is also constant between the two locations, r and $r+1$ on the surface of the subgrade from the load center. In that case Equation 4 can be written as

$$E_s(r) = 2 (1-\mu^2) a \Delta q(r) / \Delta d(r) \quad (5)$$

$$= 2 (1-\mu^2) a \{q(r) - q(r+1)\} / \{d(r) - d(r+1)\} \quad (5a)$$

Substituting the expression for $q(r)$ from Equation 3a into Equation 5a, we get

$$E_{si}(r, r+1) = 2 (1-\mu^2) a q(0) \{1/f(r) - 1/f(r+1)\} / \{d(r) - d(r+1)\} \quad (6)$$

$$E_{si}(0, r) = 2 (1-\mu^2) a q(0) \{1 - 1/f(r+1)\} / \{d(0) - d(r+1)\} \quad (6a)$$

Where, $E_{si}(r, r+1)$ and $E_{si}(0, r)$ are intra-spacing or intra-sensor surface layer moduli.

Equations 4, 6 and 6a are the three fundamental equations, Hossain-Boussinesq equations, which form the basis of determining

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layer moduli without thickness information.

For a subgrade of infinite depth using the deflections, $d(r)$ and pressure-decreasing factor, $f(r)$ values from Table 1, we get from Equations 4, 6 and 6a:

$$E_s(r) = E_{si}(r, r+1) = E_{si}(0, r+1) = 10 \text{ ksi.}$$

A few parameters are needed to determine layer modulus and thickness. These are layer and modulus influence factors, $R(n)$ and $M(n)$, respectively. These are expressed by the following equations.

Layer and Modulus Influence Factors

$$C1 = \{E_{si}(r, r+1)/E_s(r)\}^{0.26} \quad (7)$$

$$C3 = \{E_{si}(r, r+1)/E_s(r)\}^{0.26} \quad (8)$$

$$E(n) = E_{si}(0, H(n)) * C1(r) \quad (9)$$

$$R(n) = H(n) * \{E(n-1)/E(n)\}^{0.26} \quad (10)$$

$$H(n) = M(n) / C1(r) \quad (11)$$

$$M(n) = \text{Distance where } E_s(r) = E_{si}(r, r+1) \quad (12)$$

where, n is the number of layers.

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APPLICATION OF THIS METHODOLOGY IN LAYERED PAVEMENTS

In a pavement system, there are three unknowns in each layer: thickness (H), modulus (E), and Poisson's ratio (μ). Since Poisson's ratio does not vary significantly (usually range from 0.2 to 0.45) and can be assigned if the layer type is known, the actual number of unknowns in a layer are 2. Thus, in a pavement of L layers, the total number of unknowns is $(2L-1)$, since the thickness of L-th layer, half-space is infinite. However, Equation 10 indicates that the modulus (E) and thickness (H) are also related to one another through the influence factors. Equations 4 and 6 provide $(2N-1)$ information, where N is the number of sensors. These include N number of $E_s(r)$ and $(N-1)$ number of $E_{si}(r, r+1)$ values. Thus, it is possible that both the layer modulus and thickness may be determined from N number of deflections obtained from the FWD testing using these forward calculation equations. (r) and $(N-1)$ number of $E_{si}(r, r+1)$ values. Thus, it is possible that both the layer modulus and thickness may be determined from N number of deflections obtained from the FWD testing using these forward calculation equations.

Based on the current FWD sensor and plate configuration, a new method for pavement evaluation using FWD testing has been developed at the NYSDOT. This method is called Direct Estimation of Layer Moduli and Thicknesses (DELMAT) and is based on the equations presented above. To develop this method, a series of simulated pavements were used with different pavement types, layer thicknesses and moduli as shown in Table 2.

TABLE 2 SELECTION CRITERIA FOR SIMULATED PAVEMENTS

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Pavement Type	Layer Type	Layer Modulus (ksi)	Layer Numbers	Layer Thickness (inches)
Composite	HMA Overlay	200-500	4-6	4-6
	Surface	5000 (PCC) 200 -2000 (HMA)		4 - 12
PCC	Treated Permeable Base	200 -1000	2-5	4-8
HMA	Subbase	20 -50	2-5	12 -24
	Subgrade	5-50		12 -∞
	Stiff Layer	40-500		12 -∞

Deflections were calculated for all cases of pavements as shown in Table 2 using ELSYM5 [6] forward calculation program. The current FWD standard load plate ($a = 5.91''$), center pressure, $q(0) = 82$ psi, and nine sensor configurations were used in these simulated pavements. More than 100 simulated pavements were analyzed to develop this method.

The procedure to determine pavement layer moduli and thicknesses using this method are discussed in the following examples.

Two Layer Case:

This two-layer case consists of two layers: Granular subbase and subgrade. The modulus of subbase, $E(1) = 20$ ksi and thickness, $H(1) = 12$ inches. The modulus of subgrade, $E(2) = 10$ ksi.

The deflections were calculated using ELSYM5 Program with the standard nine sensor FWD load and sensor configuration. The

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deflections and DELMAT parameters are presented in Table 2.

Table 2 Two-layer Case: Subbae/Subgrade

r	d(r)	E_s(r)	E_{si}(r,r+1)	E_{si}(0,r)	E_{si}(0,r)/C3	C1	C3
inch	mils	ksi	ksi	ksi	ksi		
0.00	52.50	15.51					
8.0	26.7	12.3	18.9	18.9	16.87	1.12	1.12
12	19.4	10.7	16.5	18.4	15.9	1.12	1.15
18	13.8	9.7	13.0	17.6	15.1	1.08	1.17
24.00	10.50	9.55	10.13	17.00	14.63	1.02	1.16
36.00	6.88	9.71	9.23	16.38	14.30	0.99	1.15
48.00	5.10	9.83	9.39	16.12	14.17	0.99	1.14
60.00	4.03	9.95	9.37	15.97	14.12	0.98	1.13
72.00	3.33	10.03	9.55	15.88	14.09	0.99	1.13

As we add the subbase layer above the subgrade, its location moves downward and towards the right from the load center. The procedure for determining layer modulus and thickness for this two-layer case is outlined in the following steps.

Steps:

1. The subgrade is located at a distance from the load center where $E_{si}(0, r)/C3$ is equal to $E_s(0)$. In this case it is the layer influence distance, $R(1)$. From Table 2, the value of $R(1) = 15$ inches.
2. The modulus influence distance, $M(1) =$ the distance where $E_{si}(r, r+1) = E_s(0)$. From Table 2, $M(1) = 13.7$

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3. The modulus, $E_s(r)$ corresponding to $R_1 = 15$ in is 10 ksi which is the subgrade modulus, $E(1)$.

4. Next, the thickness of subbase, $H(1)$ is determined using the following equation

$$H(1) = R(1)/C_1 = 15/1.11 = 12.5 \text{ in.}$$

5. Using Equation 9 Table 2, we get $E(1) = \{E_{si}(0, H(1))\} * C_1 = 18.1.11 = 19.8 \text{ ksi}$

Three Layer Case: PCC Pavement

Adding a PCC surface layer on the top of the above two-layer case (Table 2), one gets a typical concrete pavement. Using the following layer thickness information, pavement deflections and associated DELMAT parameters are calculated and are shown in Table 3.

Layer No.	Modulus (ksi)	Thickness (inch)	Poisson's Ratio
1	5,000	8	0.2
2	20	12	0.4
3	10	∞	0.4

Table 3 Deflections and DELMAT parameters for three-layer PCC Pavement

r	d(r)		E_{si}(r,r+1)	Δ E_{si}(r,r+1)	E_{si}(or)/C3	E_{si}'(r,r+1)	Δ E_{si}'(r,r+1)
	mils	ksi	ksi	ksi	ksi	ksi	ksi
0	8.22	107.35					
8	7.90	41.5	1746.6	1121.8	634.8	2461.3	2211.4
12	7.65	27.0	533.8	340.6	438.5	249.9	112.4
18	7.24	18.5	193.3	116.7	288.5	137.5	103.0
24	6.81	14.7	76.5	38.6	214.2	34.5	-3.2
36	5.93	11.3	38.0	17.6	144.4	37.7	27.1
48	5.11	9.8	20.3	6.5	112.8	10.6	2.6
60	3.8	8.9	10.8	3.1	95.8	8.0	0.7
72	3.8	8.9	10.8		85.6	7.2	

The first step for a pavement engineer is to determine number of layers that exists in the pavement. This is performed using the

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following criteria:

1. Determine first the subgrade location using Step 1 as given in the 2-layer case.
2. Determine the intersections between of $\Delta E_{si}(r, r+1)$ and $E_s(r)$ or between $E_{si}'(r, r+1)$ and $E_s'(r)$. If intersections exist before the subgrade location, then the subbase layer is present. The modulus of subbase can be determined using the steps as described in the 2-layer case.
3. Then find the intersections between $\Delta E_{si}(r, r+1)$ and $\Delta E_{si}''(r, r+1)$ values. $\Delta E_{si}''(r, r+1)$ values are calculated from the revised deflections $d'(r)$ which are calculated using the following equation:

$$d'(r) = [d(r) - \{(d(r) - d(r+1)) / \{1/f(r) - 1/f(r+1)\}\}] / f(r+1) \quad (13)$$

Then calculate $E_s'(r)$, $E_{si}'(r, r+1)$, etc. in the same manner using the revised deflection, $d'(r)$ as it is performed with $d(r)$.

4. If there are intersections before the subbase intersection, then another layer exists between the surface layer and the subbase. This layer could be a bound layer such as a cement or asphalt treated permeable base. To determine the exact location of this layer, calculate the intersection(s) between $\Delta E_{si}'(r, r+1)$ and $\Delta E_{si}''(r, r+1)$ values. These intersections are the layer influence distances; $R(n)$, where n is the number of layers. From their locations the distances between these locations, $\{R(n) - R(n-1)\}$ are calculated. These distances and corresponding $C1$ values are used to determine their moduli and thicknesses using the steps as described earlier.

Using the DELMAT parameters of Table 3 in these above criteria and the steps mentioned in the 2-layer case, layer moduli and thicknesses are determined and are presented in Table 4. It should be mentioned here that the value of $C1$ for the subbase is used as 1, since high modulus surface layer tends to overestimate the subbase modulus.

Table 4 Layer Moduli and Thicknesses for 3-layer Case

Layer Type	DELMAT Parameters
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	$E_{si}(0, H(1))$ ksi	R(i), inches	Thickness(i) inches	Modulus (i), ksi	C1 (i)
Subgrade		51.5		9.8	
Subbase		33.8	14.6	20.3	1.2*
PCC	1746	22.5	8.46	4650	2.64

Note: * - The C1 value of 1.2 was not used to calculate the subbase modulus.

Four Layer Case: PCC Pavement with a Permeable Base

The layer modulus and thickness information of this 4-layer pavement system is given below:

Layer No.	Modulus (ksi)	Thickness (inch)	Poisson's Ratio
1	5,000	8	0.2
2	200	8	0.3
3	20	12	0.4
4	10	∞	0.4

Table 5 presents the deflections and DELMAT parameters.

Table 5 Four-layer PCC Pavement with Permeable Base

R	d (r)	$E_s(r)$	$E_{si}(r,r+1i)$	$E_{si}(0,r)$	$\Delta E_{si}(r,r+1i)$	$E_{si}(0,r)/C3$	$\Delta E_{si}'(r,r+1i)$
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0	7.06	124.9					
8	6.78	48.3	1883.2	1883.2	1199.4	726.5	2490.6
12	6.59	31.5	683.8	1398.4	433.9	521.5	127.6
18	6.27	21.3	249.9	933.2	148.7	349.3	135.7
24	5.94	16.9	109.7	690.5	50.6	263.1	-4.9
36	5.28	12.7	50.6	454.8	24.1	179.2	37.0
48	4.65	10.8	26.5	343.4	8.6	139.6	3.4
60	4.09	9.8	17.9	282.3	4.5	117.9	2.1
72	3.59	9.3	13.4	243.7		104.3	

Using $\Delta E_{si(r, r+1)}$ and $\Delta E_{si}'(r, r+1)$ intersection we get from Table 6, $R_1=17.7$ in, $R_2=30$ in. The distance of the subgrade from the load center, R_3 from Table 4 = 58 in. Hence there are 4 layers in this pavement system. The subgrade modulus, $E(4)$ at 58 in. = 9.9 ksi, the Subbase modulus, $E(3)$ between 44.6 and 58 inches is 21 ksi, modulus of permeable base, $E(2)$ between 18 and 33.2 inches = $101 \cdot C_1 = 101.3 \cdot 1.6 = 162$ ksi, and finally the PCC layer modulus, $E(1) = 1883 \cdot 2.6 = 4877$ ksi. These results show that permeable base modulus is found 19 percent lower than the actual value. These layer moduli and thicknesses are shown as tabulated form in Table 6.

Table 6 Layer Moduli and Thicknesses for 4-layer with Permeable Base

Layer Type	DELMAT Parameters				
	$E_{si}(0, H(i))$ ksi	$R(i)$, inches	Thickness(i) inches	Modulus (i), ksi	$C_1(i)$
Subgrade		58		9.9	
Subbase		44.6	11.5	21	1.2*
Treated Permeable Base	1746	30	7.8	162	1.6
PCC	1883	17.7	7.4	4520	2.4

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Four Layer Case: PCC Pavement with an HMA Overlay

The layer modulus and thickness information of this case is given below:

Layer No.	Modulus (ksi)	Thickness (inch)	Poisson's Ratio
1	400	6	0.3
2	4,000	12	0.2
3	20	12	0.4
4	10	∞	0.4

Table 7 presents the deflection and parameters for this four-layered pavement. The $E_{si}(r, r+1)$ values show that the sublayer modulus $E_{si}(8, 12)$ is greater than that of $E_{si}(0, 8)$ indicating the presence of a higher modulus layer below the existing surface layer. To clarify this, we can use the following equation to reveal the nature of the buried high modulus layer:

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$$E_{sb}(r, r+1) = 2 (1-\mu^2) a * \{(q(0)/f(r)) / \{d(r) - d(r+1)\}\} \quad (14)$$

Table 7 Four-layer PCC Pavement with HMA Overlay

r	d (r)	E_s(r)	E_{si}(r,r+1i)	E_{sb}(r,r+1)	Δd(r)	E_{si}(0,r)/C3	Δda'(r)	C1(r)
0	6.3	140.0						
8	5.3	61.8	527.3	505.9	1.00	302.0	-0.40	1.75
12	5.1	40.3	814.2	1718.2	0.16	285.1	-0.02	2.18
18	5.0	26.7	568.8	1257.3	0.14	256.3	0.23	2.21
24	4.8	20.7	208.8	775.7	0.16	228.0	0.24	1.82
36	4.5	14.9	92.8	241.3	0.36	184.0	0.39	1.61
48	4.1	12.2	45.2	167.7	0.37	154.8	0.33	1.41
60	3.8	10.7	27.8	134.1	0.36	134.9	0.31	1.28
72	3.4	9.8	19.1	112.8	0.35	120.8		

The values of $E_{sb}(r, r+1)$ in this case are shown in Table 8. The columns $E_{sb}(r, r+1)$ and $\Delta d(r)$ show the breaks of the layers of this pavement. Using these breaks and C1 values, we can determine the moduli and thicknesses of the subgrade and subbase layers using the procedure mentioned above. However, the overlay and the underlying PCC layer need a special procedure to determine their moduli and thicknesses. This is described below.

Table 8 Layer Moduli and Thicknesses for 4-layer with Overlay

Layer Type	DELMAT Parameters				
	E_{si}(0, H(i)) ksi	R(i), inches	Thickness(i) inches	Modulus (i), ksi	C1 (i)
Subgrade		72*		9.8	

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Subbase		56.8**	12.7	19.1	1.19
PCC	1718#	30	11.56	3797	1.7
HMA Overlay	500	10.35	5.9	500	1.75

Notes: -* The intersection between $E_s(r)$ and $\{E_{si}(r, r+1) - E_s(r)$ is used in this case.

-** Intersection of $\Delta E_{si}(r, r+1)$ and $E_s(r)$ gives 56.8 inches.

-# In this case the value of E_{sb} (8, 12 in) is used.

The first break in column $\Delta d(r)$ is at 12 inches. The corresponding C1 value is 2.18. The Thickness of HMA overlay = $12/2.18 = 5.5$ inches. The modulus of overlay, $E(1) = 505$ ksi which is 25 percent greater than the actual value of 400 ksi. A reduction factor can be used in this case. The modulus of the PCC layer can be determined using the following equation:

$$E_b(8, 12) * C1 = 1718 * 2.18 \text{ ksi} = 3745 \text{ ksi which is almost equal to 4000 ksi.}$$

Alternatively, the thickness of PCC layer can also be determined from the intersection of $E_{si}(r, r+1)$ and $E_{si}(0, r)$ and then subtracting HMA layer thickness. In this case it is $(18-6) = 12$ inches.

Stiff Layer

A stiff layer exists below the subgrade when $E_s(r)$ increases with the increase of distance from the load center. In this case, the subgrade modulus may be significantly overestimated if determined using the above procedure. Therefore, it is necessary to correct the deflections to account for the effect of the stiff layer. This is performed by locating first the subgrade by calculating the distance where the surface moduli, $E_s(r+1) - E_s(r) = 0$. A method to correct these deflections is presented below in the Filed Test Sites Section.

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FIELD TEST SITES

Table 9 presents the site information including locations, layer material descriptions and thicknesses. The layer thicknesses are obtained through coring and drilling using NYS standard procedures. The boring depth in all cases was about 48 inches from the surface. Dense silty/sandy Gravel with blow counts (N value) greater than 50 were encountered at or below 48 inches in all cases indicating presence of stiff layer within close proximity to the subgrade surface. The FWD testing was performed prior to the coring and drilling operations. Pavement cores and soil samples from these sites were brought to the Main Office for thickness measurement and testing of soil samples.

Figure 1 presents the deflection measurements obtained from FWD testing from these sites. Figure 3 shows the plot of $E_s(r)$ values for these four sites. Figure 3 reveals that $E_s(r)$ values start increasing after about 40 inches from the load center in all sites. This indicates presence of a stiff layer below the subgrade. Therefore, these deflections are corrected (Figure 2) to determine layer moduli and thicknesses using the procedure as outlined in the next section. These steps for Route 9N are presented in Table 10. The intersection of $E_s(r)$ and $E_{si}'(r, r+1)$ in these plots roughly indicate the location of subbase layers.

From the deflections and load information, moduli and thicknesses of the pavement layers for these sites are determined using the same technique as discussed in Example 1 above. Table 11 presents the calculated layer moduli and thicknesses for four sites. In order to compare these moduli, MODCOMP5 backcalculation Program was used to determine layer moduli from the known thickness information. These backcalculated moduli are also presented in Table 11 for comparison.

TABLE 10 LAYER INFORMATION OF THE FILED SITES

ID	Route Number	Region	County/Town	Road Marker	Description of Layer Materials	Layer Thicknesses
C1	Route 9N	1	Saratoga/ Greenfield	9N-1501-2015 NB	TMA	202
					S14r Sand Subbase	201
					S14r Gravel Subbase	
C2	Route 75	5	Erie/ Hamburg	75-5301-1187 NB	TMA	266.7
					Asphalt Treated Base	101.6
					Crusally Sand Subbase	111.5
					Crusally Sand Subbase	
C3	Route 222	3	Cortland/ Cortlandville	222-3202-1023 EB	TMA	170
					S14r Sand Subbase	157
					S14r Gravel Subbase	
C4	Route 17	6	Steuben/Corning	17-6404-2104 EB	PCC	279.4
					Cement Treated Base	101.6
					Gravel and Sand	522
					S14r Gravel Subbase	

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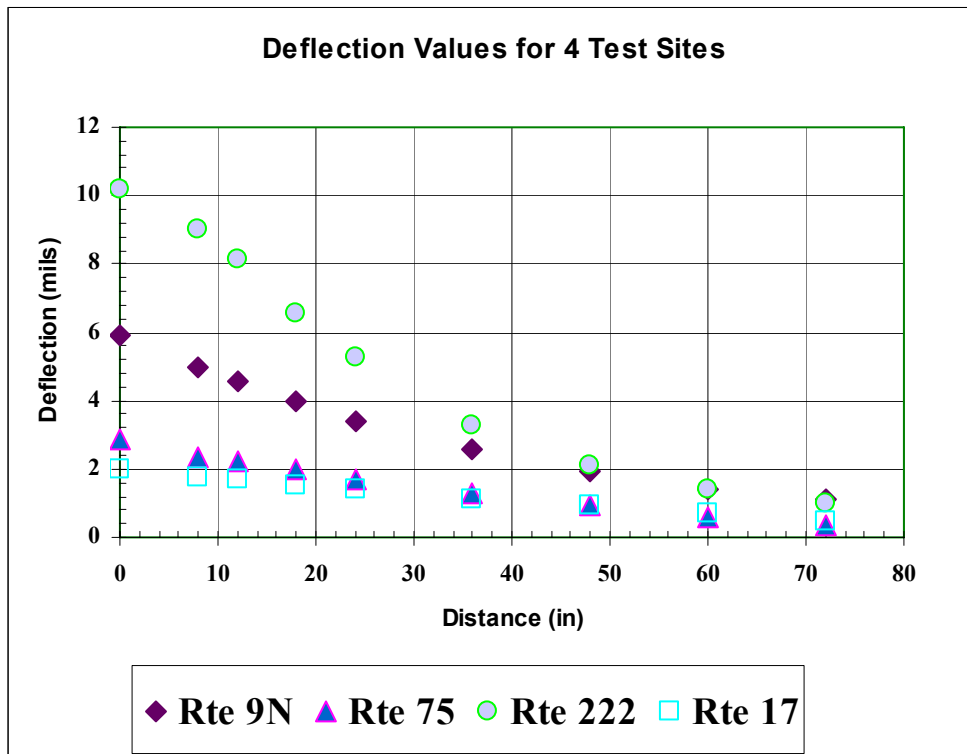


Figure 1 Measured Deflection for the Four Field Sites

Correction for Deflections

A procedure to correct the measured deflections for Rte 9N is described in Table 10 using the following steps:

- a) Calculate $\Delta d(r)$ from the $E_{si}(r, r+1)$ values, where

$$\Delta d(r) = [\{d(r) - d(r+1)\} / \{1/f(r) - 1/f(r+1)\}] * 2 / \{f(r) + f(r+1)\}$$

- b) Perform the cumulative summation, $\sum \Delta d(r)$. Read the this value at R (n) and use this as the new deflection at the load center, say $d^1(0)$.
- c) Using this $d^1(0)$, recalculate the other deflections, $d^1(r)$ and corresponding $E_S^1(r)$ values.
- d) Then calculate the new $E_{si1}(r, r+1)$ values, using the relationship

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$$E_{si1}(r, r+1) = E_{si}(r, r+1) * [E_s^1(r) / E_s(r)]^{0.26}$$

- e) Using these new $E_{a1}(r, r+1)$ values repeat the steps (a) through (d) until the difference between $d^n(0)$ and $d^{n-1}(0)$ is almost equal to 0.
- f) Use the last $D_n(0)$ and $E_{si}^{n-1}(r, r+1)$ values to calculate layer moduli and thicknesses.

Table 10 Procedure to Correct Deflection Data for Route 9N

r (in)	0	8	12	18	24	36	48	60	72
f (r)	1	2.49	3.93	6.09	8.12	12.18	16.24	20.30	24.37
d (r), mils	5.92	4.97	4.54	3.97	3.42	2.59	1.91	1.42	1.09
d_{isc} (r)		0.91	0.91	1.26	1.89	1.99	2.33	2.18	1.80
∑ d_{isc} (r)		0.91	1.82	3.08	4.96	6.96	9.29	11.47	13.27
d'(r)	12	11.05	10.62	10.05	9.50	8.67	7.99	7.50	7.17
d_{isc}'(r)		0.91	0.91	1.60	2.46	2.73	3.38	3.36	2.94
∑ d_{isc}'(r)		0.91	1.82	3.42	5.88	8.61	11.99	15.35	18.29
Corr. d(r)	11.5	10.55	10.12	9.39	8.68	7.54	6.55	5.80	5.26

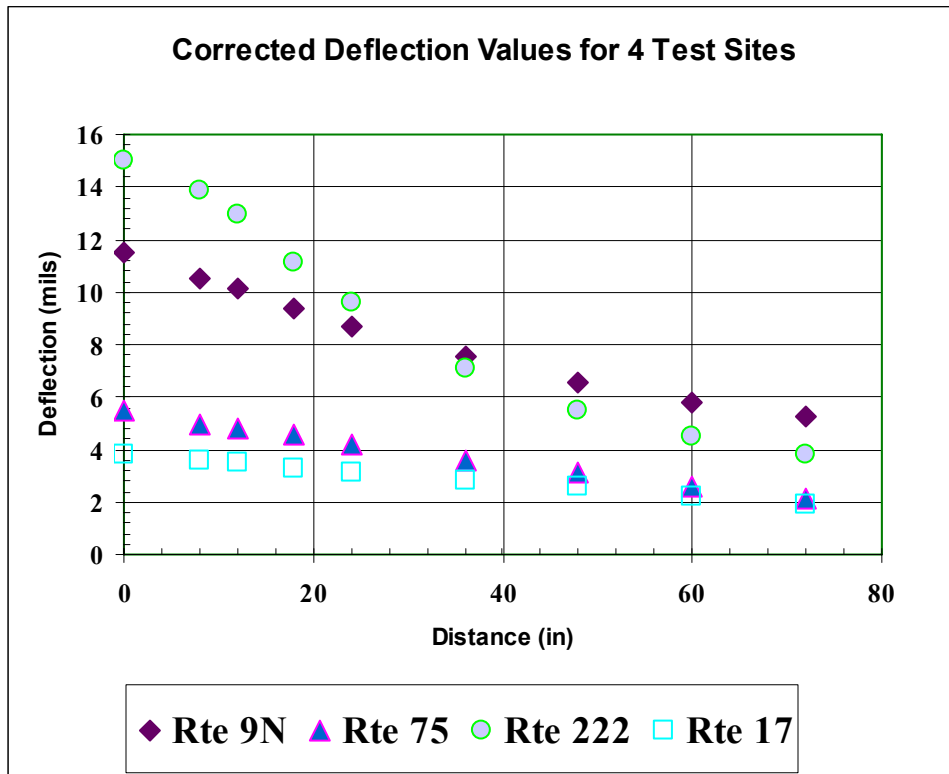


Figure 2 Corrected Deflections for the Four Field Sites

Stiff Layer Location and its Modulus

The stiff layer is located at a distance, $R(n+1)$ where $\Delta E_{si}(r, r+1) = 0$. If this zero does not occur within the measured deflections, the stiff layer is located outside the outer most sensor location. In that case, the stiff layer location may be determined from a plot of $\Delta E_{si}(r, r+1)$ versus distance, r . The distance, r where $\Delta E_{si}(r, r+1)$ intersects the x-axis (distance) is the location of the stiff layer. Alternatively, an equation can be written in terms of $\Delta E_a(r, r+1)$ and r . This equation can be solved for r where $\Delta E_{si}(r, r+1) = 0$. The modulus of stiff layer is determined using the same procedure for locating the stiff layer. The modulus is calculated from the $E_s(r)$ at $R(n)$.

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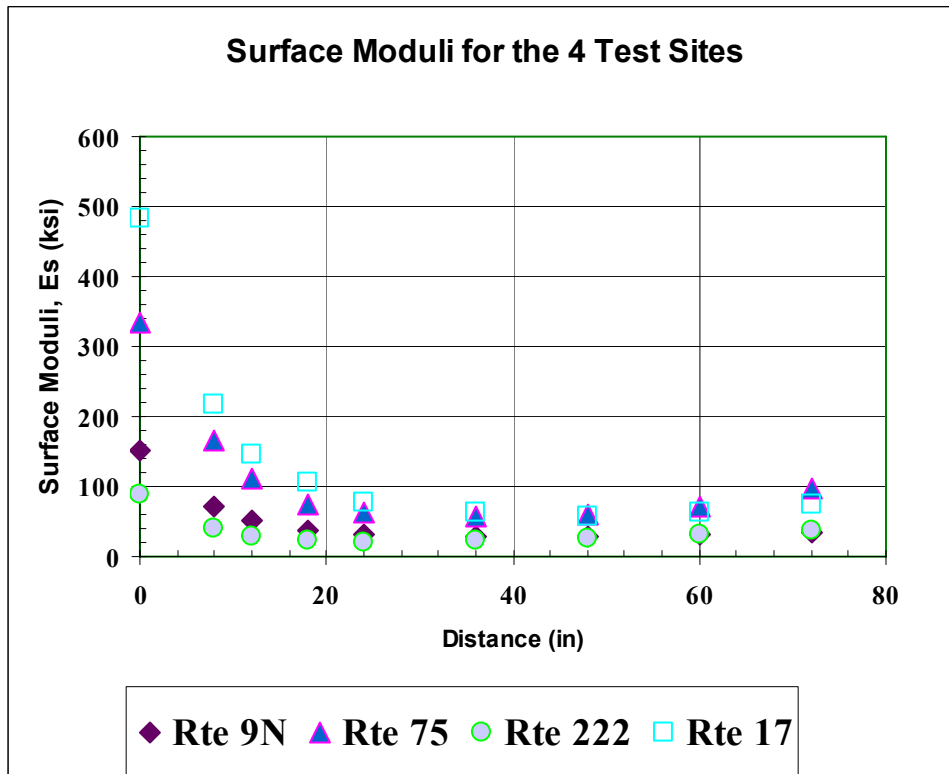


Figure 3 Surface Moduli, $E_s(r)$ for the Four Field Sites

When the stiff layer is present within the measured deflections, its modulus is calculated from the relationship: $E(n+1) = E_s\{R(n+1)\} * \{\text{corrected } d(r)/d(r)\}$.

Comparison of Moduli

The presence of stiff layer close to the subgrade surface created some problem in executing the MODCOMP5 program [6]. Several runs were needed to obtain reasonable results. Except C-1 (Route 9N), the RMS error was more than 2%. When a stiff layer is present at shallow depth, the MODCOMP5 program has a tendency to yield higher subgrade modulus. This occurred in the C-2, C-3, and C-4 sites. The stiff layer modulus and its approximate location were determined in each case using DELMAT method. The results are shown in Table 12. The locations of the stiff layers except C-3 are beyond the outer most sensor location of 72 in. In the case of the surface and asphalt treated subbase layers, the moduli determined using MODCOMP5 program compared well with those using DELMAT, except for the C-3 site. In the case of C-3 site, the asphalt layer modulus using MODCOMP5 is about 1.5 times than the that of DELMAT value. This maybe attributed to the stiff layer which is located within the measured deflections. The moduli of the subbase and the subgrade layers are not compared well because of the

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overestimation of subgrade moduli by MODCOMP5 program.

Comparison of Thicknesses

The layer thicknesses obtained using DELMAT are compared against the measured thicknesses. The measured layer thicknesses are shown in Table 4 with the moduli backcalculated using the MODCOMP5 program. The DELMAT thicknesses compared well against the core samples of surface and asphalt treated base layers. The maximum difference is less than 12 percent. In case of subbase and subgrade layers, thicknesses are less compared. This is because of the fact that in NYS both the subbase and upper subgrade soils consist of granular course aggregates and sands. Only difference is that the subgrade soils contain more fines. Therefore, identification of their boundaries may be difficult.

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Table 12 Calculated Moduli and Thicknesses from the Four Field Sites

ID		MODCOMP5 Moduli					DELMAT Moduli and Thicknesses				
		Asphalt	Asphalt Treated base	Granular Subbase	Subgrade	Stiff Layer	Asphalt	Asphalt Treated base	Granular Subbase	Subgrade	Stiff Layer
C1	Thickness, In	11.5	-	15	36	-	10	-	12.7	66	-
	Modulus, ksi	845	-	47.5	16.5	46.5	822	-	38	17.8	60
C2	Thickness, In	10.5	4	17.5	-	-	10.2	5.1	16	54.5	-
	Modulus, ksi	2200	337	24.4	82.5	-	2070	395	38	17	1400
C3	Thickness, In	7.0	-	18.0	-	-	7.4	-	14.3	32.2	-
	Modulus, ksi	1460	-	7.4	36.3	-	1130	-	25.0	10.5	45
C4	Thickness, In	11.0	4.0	21.0	-	-	12.0	4.0	12.0	126.0	-
	Modulus, ksi	4080	1060	26.5	85.5	-	4300	920	50	16	80

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CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are made based on the results of this study.

- A new forward calculation method called DELMAT, based on FWD deflection testing, has been developed for determining pavement layer modulus and thickness. This method is developed based on the Hossain-Boussinesq equations.
- This method does not require any seed moduli as required by many of the backcalculation programs. This gives the user more flexibility to determine the structural condition of the underlying layers, including the presence of any overlay, bound layer or a stiff layer in the pavement. More than 100 simulated pavements were used to determine this method. The deflections of these pavements were determined using forward calculation program ELSYM5.
- The moduli and thicknesses using this method are determined from the deflection basins obtained from the four NYS sites. The moduli values are compared against those obtained using MODCOMP5 backcalculation program. The thicknesses are compared against the measured thicknesses of the cores and soil samples. Overall the DELMAT moduli and thicknesses compared satisfactorily with regard to the surface and asphalt treated base layers against the MODCOMP5 and core thicknesses, respectively. The fair comparison for the subbase and subgrade layers can be attributed to the presence of shallow stiff layer. The MODCOMP5 moduli for the subbase and subgrade soils in that case may not be accurate due to RMS error greater than 2 percent.
- Presence of the stiff layer can be detected using this method. Its location and modulus can be determined. When a stiff layer is present, the deflections need to be corrected to determine the moduli and thicknesses of the layers above the stiff layer, especially for the subbase and subgrade layers. This technique for the correction of deflections allows the engineer to determine moduli and thicknesses of the pavement layers irrespective of the presence of the stiff layer.
- The presence of an asphalt overlay over a PCC pavement can be detected using DELMAT. The modulus and thickness of the overlay can also be estimated.

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REFERENCES

1. W. Uddin, A. H. Meyer, W. R. Hudson, and K. H. Stokoe II, "Project-Level Structural Evaluation for Pavements Based on Dynamic Deflection," Transportation Research Record 1007, TRB, National Research Council, Washington, D. C., 1985, pp. 37-45.
2. A. J. Bush III and R. D. Alexander, "Pavement Evaluation Using Deflection Basin Measurements and Layered Theory." Transportation Research Record 1022, TRB, National Research Council, Washington, D. C., 1985, pp. 16-29
3. B. E. Sebaaly, M. S. Mamlouk, and T. G. Davies, "Dynamic Analysis of Falling Weight Deflectometer Data." Transportation Research Record 1007, TRB, National Research Council, Washington, D. C., 1985, pp. 37-45.
4. M. M. Hossain, "A Rigorous Method for Structural Evaluation of Pavement from Deflection Measurements," Proceedings of the International Conference on Highway Pavement Data, Analysis and Mechanistic Design Applications, Columbus, Ohio; September, 2003.
5. R. E. Sherrif and L. P. Geldart, "Exploration Seismology," Volume 1: History, Theory and Data Acquisition. Cambridge University Press, 1995.
6. FHWA, "ELSYM5 User's Guide," 1985.
7. L. H. Irwin and T. Szebenyi, "User's Guide to MODCOMP3 Version 3.2. CLRP Report 91-4, Cornell University Local Road Program, Ithaca, N. Y., and March 1991.