

IN THE QUEST OF DETERMINING PAVEMENT LAYER MODULI AND THICKNESSES FROM FWD TESTING WITHOUT BACKCALCULATION

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ABSTRACT

A method of estimating pavement layer moduli and thicknesses directly from nondestructive (NDT) deflection testing has been under development at the NYSDOT. This method is fast and requires no backcalculation techniques for deflection analysis. It is developed from pressure distribution factors (f) at sensor locations based on deflection data obtained in an elastic half-space with known modulus of elasticity. Using Boussinesq equation, sensor modulus (E') and intrasensor modulus (E'') are calculated from the pressure distribution factors (f). These values of E' and E'' at different distances from the load center are used to estimate the layer moduli. A similar technique is used to estimate the layer thicknesses from the plots of E' and E'' versus sensor distances.

Pavement layer moduli and thicknesses determined by the new method were validated. Case studies from New York State DOT falling-weight deflectometer (FWD) testing are presented to demonstrate applicability of the new method. Most importantly, all computations are made with a spreadsheet program requiring no sophisticated computer program. This method provides state highway agencies a useful tool in analyzing NDT deflection data.

INTRODUCTION

Nondestructive testing (NDT) on pavements is having a significant impact on design and evaluation of pavement systems. To determine the layer moduli of a pavement system deflection measurements from NDT testing are commonly performed.

The deflection basin measurements may be made by static loading (Benkelmann Beam), by steady state vibratory loading, or by impact loading such as Falling Weight Deflectometer (FWD). The FWD is a device that applies an impact loading to the surface of the pavement. Sensors at the location of loading and at fixed radii from the load center are used to measure the deflections. The resulting set of deflections is known as the deflection basin. Much background information on this method has been given in the literature. Special computer programs are used to calculate a modulus profile for the pavement system from the peak values of measured input force and resulting deflection basin.

At present most highway agencies are using FWD method for pavement evaluation. However, the available techniques for backcalculation of layer moduli require accurate layer thickness information. Pavement coring to determine layer thickness is sometimes difficult and time consuming. Using Ground Penetrating Radar (GPR) technique to determine layer thickness is

costly and a skilled person is required for data interpretation. The method presented in this paper offers an alternative by using FWD deflection data to rapidly estimate the layer moduli and thicknesses of pavement in the field.

DESCRIPTION OF METHODOLOGY

The calculation of a layer modulus using this new method is based on determining the following three parameters:

- Pressure distribution factors at sensor locations (f)
- Modulus at sensor (E') and in-between sensors locations (E'')
- Layer influence factor (I)

A brief description of each parameters is given below.

Pressure Distribution Factors at Sensor Locations (f)

When a dynamic impulsive load is applied through a plate of known radius on the surface of a half-space, the induced pressure, q (load/plate area) decreases in horizontal direction 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 losses by absorption when the motion is associated with low frequencies and short distances. Thus, the pressure distribution factor (f) at a distance (r) from the load center in horizontal direction on the surface of a half-space is calculated by consideration of geometrical spreading only. This factor is defined as the ratio between the pressure at the load center (q_0) and the pressure (q_i) at a distance (r_i) and is determined as:

$$f_i = q_0 / q_i \quad (1)$$

To determine q_i , a series of deflections (d_i) at distances (r_i) are calculated for a half-space with known modulus of elasticity (E) using ELSYM5 computer program [6]. The values of E, pressure (q_0), plate radius (a) and Poisson's ratio (μ) are taken as 690 MPa, 563.4 kPa, 150 mm and 0.2, respectively. The resulting deflections (d_i) at corresponding distances (r_i) are shown in Table 1.

TABLE 1: PRESSURE DISTRIBUTION FACTORS (f_i)

r_i (mm)	0	75	150	200	300	450	600	900	1200
d_i (micron)	236.2	220.2	145	95	60.2	39.37	29.2	19.38	14.66
f_i	1	1.073	1.629	2.487	3.924	6	8.087	12.19	16.12

The factors f_i are obtained by dividing d_0 with d_i . A plot of these factors against r_i/a is shown in Figure 1. Figure 2a indicates that when r_i/a is greater than 2, f_i may be approximately determined

as:

$$f_i = r_i / (a/2) = 2 r_i / a \quad (2)$$

These factors allow to calculate q_i at any distances from the load center.

Modulus at Sensor (E'_i) and Intra-Sensors Locations (E''_i)

The modulus E_0 of a linear elastic half-space due to a vertical pressure q_0 on a flexible plate resulting deflection d_0 at the load center can be calculated using the following Boussinesq equation:

$$E'_0 = 2 (1-\mu^2) a (q_0 / d_0) \quad (3)$$

Since in half-space, E is constant at any location, Eq. (3) can be generalized as follows:

$$E'_i = 2 (1-\mu^2) a (q_i / d_i) \quad (4)$$

Where q_i is the pressure at r_i . Substituting Eq. (1) in Eq. (4), we get

$$E'_i = 2 (1-\mu^2) a q_0 / (f_i d_i) \quad (5)$$

This is the generalized form of equation (3) at any distance (r_i) from the load center on the surface of a half-space. Boussinesq equation can also be used to calculate modulus E'_j between two locations (or sensors) on the surface as shown in the following equation:

$$\begin{aligned} E''_j &= 2 (1-\mu^2) a q_i / d_i = 2 (1-\mu^2) (q_i - q_j) a / (d_i - d_j), j > i \\ &= 2 (1-\mu^2) a q_0 (1/f_i - 1/f_j) / (d_i - d_j) \end{aligned} \quad (6)$$

Equation (6) converges to Eq. (5) when $f_j \rightarrow \infty$, since $d_j \rightarrow 0$ when $f_j \rightarrow \infty$. Equations (5) and (6) can be viewed as at-sensor and intra-sensor modulus, respectively. For a half-space these values are equal, but for a layered system they are different and can be used to determine layer modulus. Substituting Eq. (2) and using $q_0 = P_0 / (p a^2)$, where $P_0 =$ applied load, Eqs. (5) and (6) takes the following form:

$$E'_i = [(1-\mu^2)/p] P_0 / (r_i d_i) \quad (7a)$$

$$E''_j = [(1-\mu^2)/p] P_0 (1/r_i - 1/r_j) / (d_i - d_j), j > i \quad (7b)$$

Equation (7a) is identical with AASHTO Equation for Subgrade Modulus, $M_r = 0.24 P_0 / (r_i d_i)$ when $\mu = 0.5$ [7]. Equation (5) and (6) can be expressed in the following forms:

$$\begin{aligned} E'_i &= 2 (1-\mu^2) a (q_0 / f_i d_i) = 2 (1-\mu^2) a (q_0 / d_0) / [(f_i d_i) / d_0] \\ &= E_0 / F'_i \end{aligned} \quad (8)$$

and

$$\begin{aligned} E''_j &= 2 (1-\mu^2) a q_0 (1/f_i - 1/f_j) / (d_i - d_j), j > i \\ &= 2 (1-\mu^2) a (q_0 / d_0) / [(d_i - d_j) / (d_0/f_i - d_0/f_j)] = E_0 / F''_j \end{aligned} \quad (9)$$

where

$$F'_i = (f_i d_i) / d_0 \text{ and} \quad (10a)$$

$$F''_j = (d_i - d_j) / (d_0/f_i - d_0/f_j), \quad j > i \quad (10b)$$

are at-sensor and intra-sensor modulus ratios, respectively. F'_i and F''_j can also be called stiffness ratios. Plots of these F'_i and F''_j values versus sensor distances reveal important relative stiffness characteristics of underlying pavement layers.

Layer Influence Factor (I)

The layer influence factor (I) is given by the following equation:

$$I_n = R'_n / H_n, \quad n = \text{layer number } 1, 2, 3, \text{ etc.} \quad (11)$$

where R'_n is the distance from the load center to a distance where $F'_i = F''_j$, starting with the F'_0 for layer 1, and H_n is the layer thickness.

DETERMINATION OF LAYER MODULI

Surface Layer

A typical pavement system consists of layers of PCC or AC surface, unbound subbase and subgrade. The modulus of elasticity and thickness of surface layer usually vary from 1,500 to 40,000 MPa and 100 to 300 mm, respectively. The modulus of underlying subbase and subgrade vary from 40 to 300 MPa. In such cases, the modulus ratio between the surface layer and subbase is very high and generally greater than 20. Because of this high ratio, the deflection changes at shorter distances from load center during FWD testing are associated mostly with the surface layer and are less influenced by the underlying layers. This allows one to estimate the surface layer thickness and modulus without any information of underlying layers.

Modulus of Surface Layer (E) When Thickness (H) is Known

It has been found by the authors that the full deflection associated with the surface layer is achieved within a horizontal distance of $(2/3)H$ from the load center, where H is the thickness of surface layer. In the absence of a sensor located at $(2/3)H$, a linear interpolation between sensor spacings may be necessary to calculate this deflection. Using the deflection change between the load center and $(2/3)H$, the modulus E can be estimated as:

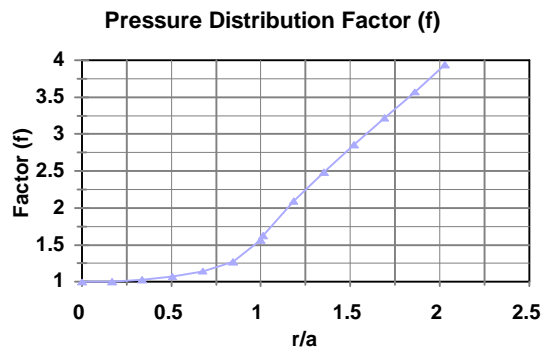
$$E = 2 (1 - \mu^2) (q_0) a / (d_0 - d_{2/3H}) \quad (12)$$

Thickness of Surface Layer

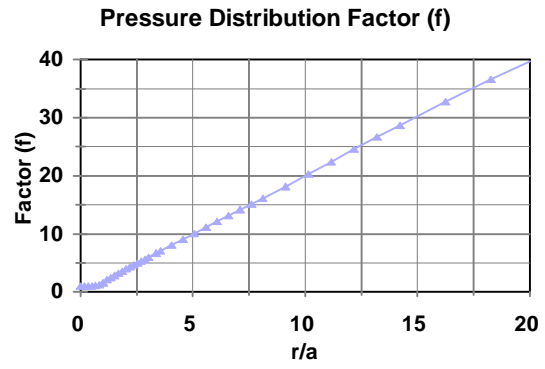
To estimate the thickness (H) of surface layer, a thickness parameter t_{i+1} is calculated as functions of f_i , d_i and r_{i+1} :

$$t_{i+1} \frac{\begin{pmatrix} \frac{f_{i+1}}{f_i} & 1 \\ \frac{d_i}{d_{i+1}} & 1 \end{pmatrix}}{\begin{pmatrix} \frac{f_{i+1}}{f_i} & 1 \\ \frac{d_i}{d_{i+1}} & 1 \end{pmatrix}} \begin{pmatrix} r_{i+1} \\ a \end{pmatrix} \quad (13)$$

The horizontal distance r_{i+1} at which t_{i+1} reaches its maximum value is assumed to be the thickness of the PCC surface layer H . However, the accuracy of calculated thickness depends on the sensor spacing and plate radius relative to the layer thickness. The current FWD sensor spacing configuration uses 200 mm spacing between first two sensors. Therefore, it is not possible to estimate PCC surface thickness less than 200 mm without interpolation.



(a)



(b)

Figure 1. Pressure Distribution Factors (f)