Structural Evaluation of Airfield Pavement Using Finite Element Analysis Based Methodology

Richard Ji

***Abstract*—**Nondestructive deflection testing has been accepted widely as a cost-effective tool for evaluating the structural condition of airfield pavements. Backcalculation of pavement layer moduli can be used to characterize the pavement existing condition in order to compute the load bearing capacity of pavement. This paper presents an improved best-fit backcalculation methodology based on deflection predictions obtained using finite element method (FEM). The best-fit approach is based on minimizing the squared error between falling weight deflectometer (FWD) measured deflections and FEM predicted deflections. Then, concrete elastic modulus and modulus of subgrade reaction were back-calculated using Heavy Weight Deflectometer (HWD) deflections collected at the National Airport Pavement Testing Facility (NAPTF) test site. It is an alternative and more versatile method in considering concrete slab geometry and HWD testing locations compared to methods currently available.

***Keywords*—**Nondestructive testing, Pavement moduli backcalculation, Finite Element Method, FEM, concrete pavements.

I. Introduction

CONCRETE pavements have long been used in the airfields due to its excellent load-carrying capacity and relatively long service life. Their performance under the combined action of load and environmental factors is essential to the amount of maintenance needed, and the remaining life and overlay thickness. The major parameters indicative of pavement performance are the material moduli of pavement layers, it is an important input in airport pavement thickness design [1].

Rigid pavements are generally analyzed as slab-on-grade structures [2]. The algorithms specifically developed for rigid pavements are based on PCC slab on elastic foundation or dense liquid foundations. There are two widely used computer-based closed-form solutions available for back-calculation of rigid-pavements properties. They are the ILLI-BACK [3] developed at the University of Illinois and the NUS-BACK [4] developed by the National University of Singapore, respectively. The first one is for AREA method-based procedures, while the other is used for best fit-based procedures. The AREA method, described in the 1993 AASHTO Guide [5], estimates the radius of relative stiffness as a function of the AREA under the deflection basin. This estimation, along with the subsequent calculation of subgrade k and slab modulus of elasticity, E, is made using simple closed form equations. The Best Fit method solves for a combination of the radius of relative stiffness and the coefficient of subgrade reaction that produce the best possible agreement between the predicted and measured deflections at each sensor. These two concrete pavement backcalculations are based on the solution of interior loading and infinite slab [6]. These close form solutions are simple and straight forward; however, it does not consider concrete slab size, and its joint condition, therefore AASHTO 1998 [7] backcalculation algorithm improves the previous backcalculation results by considering slab size. Nevertheless, the relationship between AREA and radius of relative stiffness is still based on estimated empirical correlation. It limits the development of the backcalculation accuracy of concrete and subgrade moduli from F/HWD deflection measurements.

The HWD is a Nondestructive Test (NDT) equipment used to assess the structural condition of airfield pavement systems. This paper presents an iteration-based approach for nondestructively estimating the stiffness properties of rigid airfield pavements subjected to HWD tests that were routinely conducted on Portland Cement Concrete (PCC) at the Federal Aviation Administration's (FAA's) NAPTF.

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II. Objective

The objectives of this research were to:

- Identify and statistically characterize the variation of HWD deflection data collected in F/HWD round up concrete pavement test site tested on April 2018;
- Develop a rational backcalculation method of concrete pavement for design purpose;
- Validate developed backcalculation methodology by means of comparing with existing method and other testing results.

III. Research Approach

A. FEM in Analysis of Rigid Pavement

The multi-slab model and load transfer mechanisms is from ILLISLAB [8] and DYNA-SLAB [9]. A procedure based on the FEM is presented to analyze the model of discontinues concrete pavement. In the finite element idealization, the four-nodded, rectangular plate element [10] with three degrees of freedom (DOF) at each node, namely, vertical displacement (w), rotation about the x-axis (θ_x) and rotation about the y-axis (θ_y) is used to model the rigid pavement. The matrix equation governing the multi-slab resting on foundation can be expressed in the form:

$$\{[K]_{slab} + [K]_{foundation}\}\{X\} = \{F\} \quad (1)$$

in which, $[K]_{slab}$ overall stiffness matrix of the slab, $[K]_{founadtion}$ overall stiffness matrix of the foundation. The force vector $[F]$ can be expressed by the following equation:

$$\{F\} = \int_A [N]^T q(x, y) dA \quad (2)$$

where $q(x, y)$ is the force acting on the pavement due to the HWD.

B. Backcalculation Using a Modified Newton Method

In the FWD responses, the peak deflection reflects the stiffness of the pavement. Therefore, only the peak deflections at each sensor are used in the backcalculation algorithm. The vector of measured responses is$\{U\} = [w_1^m \quad .... \quad w_4^m]^T$, where $w_i^m$is the measured surface deflection at sensor i.

The unknown properties of pavement layer i are taken to be the slab modulus E and modulus of subgrade reaction K, respectively. The vector of unknowns becomes $\{x\} = \{E_{slab} \quad K_{foundation}\}^T$.

Following the derivation by Harichandran et al. [11] and Ji et al. [12], the increment to the unknown parameters in iteration *i*, *{Δx}ᵢ*, is obtained by solving the linear set of equations

$$\{\hat{U}\}^i + [G]^i \{\Delta x\}^i = \{U\} \quad (3)$$

where $\{\hat{U}\}^i$ is the vector of deflections using the estimates of the pavement layer properties at iteration *i*, and $\{G\}^i$ is the gradient matrix at iteration *i* given by

$$[G]^i = \left[\frac{\partial\{U\}}{\partial\{x\}} \right]_{\{x\}=\{\hat{x}\}^i} \quad (4)$$

where the partial derivatives in the gradient matrix will be evaluated numerically using

$$\left.\frac{\partial U_j}{\partial x_k}\right|_{\{x\}=\{\hat{x}\}^i} = \frac{U_j\left([R]\{\hat{x}\}^i\right) - U_j\left(\{\hat{x}\}^i\right)}{r\hat{x}_k^i}, \quad j = 1,2,3,4 \quad , k = 1,2 \quad (5)$$

where U is the HWD peak deflection and x is the layer parameter (concrete modulus and modulus of subgrade reaction). [R] is a diagonal matrix with the k^{th} diagonal element being (1 + r) and all other elements being 1. A separate call to the forward concrete pavement calculation program (FEM) is required to compute the partial derivatives in each column of the gradient matrix.

Since there are more equations than unknowns in (3), more robust method for solving the problem is to use the singular value decomposition (SVD). This algorithm has been implemented in the program.

After the increments $\{\Delta x\}^i$ are obtained by solving (3), the revised moduli are obtained from:

$$\{x\}^{i+1} = \{x\}^i + \{\Delta x\}^i \quad (6)$$

The iteration is terminated when the changes in layer moduli and thicknesses are smaller than a set of specified tolerances:

$$\frac{\hat{E}^{i+1} - \hat{E}_1^i}{\hat{E}_1^i} \le \varepsilon_1 \qquad \frac{\hat{K}_k^{i+1} - \hat{K}_k^i}{\hat{K}_k^i} \le \varepsilon_1 \quad (7)$$

C. Program FEMBACK

The backcalculation computer program FEMBACK was developed according to the above algorithm. The slab deflection calculations are based on the assumption of the plate theory on a liquid foundation. The program is intended to backcalculate modulus using HWD deflection basin test data at user's desirable location for rigid pavements. It can consider the various HWD test on different PCC slab location. The source files are written using the Microsoft FORTRAN complier version 4.0.

D. Closed-Form Backcalculation for Concrete Pavement

Westergaard [13] regarded the slab-on-grade problem to follow the classical medium-thick plate theory. In this idealization, the subgrade is characterized using a single parameter known as the modulus of subgrade reaction or simply the *k* value. This continues to be a popular idealization even today although pavements are now constructed on more substantial foundations. Westergaard also introduced the radius of relative stiffness, this parameter measures the stiffness of the slab relative to that of the subgrade and has linear dimensions.

$$l = \left[\frac{Eh^3}{12(1-\mu^2)k} \right]^{0.25} \quad (8)$$

where: l = radius of relative thickness, E = modulus of elasticity of the PCC slab, h = slab thickness, μ = Poisson's ratio, k = modulus of subgrade reaction.

Ioannides et al. [14] made an in-depth evaluation of the various Westergaard equations and determined that several equations ascribed to Westergaard in the literature are erroneous. They proceeded to conclusively establish the correct forms of the equations. Rigid pavements are generally analyzed as slab-on-grade structures.

Darter [2] and The 1993 AASHTO Guide [5] estimates the radius of relative stiffness as a function of the AREA under the deflection basin. This estimation, along with the subsequent calculation of subgrade k and slab modulus of elasticity, E, is made using simple closed form equations. Losberg's deflection equation through direct integration of Bessel function for radial distance of 0, 305, 610, 915 mm (0, 12, 24, 36 inches) and the following regression model was developed:

$$l = \left[\frac{ln\left(\frac{36-AREA}{1812.279}\right)}{-2.559340} \right]^{4.387009} \quad (9)$$

where l = radius of relative thickness

$$AREA = 6[1 + 2\frac{w_1}{w_0} + 2\frac{w_2}{w_0} + \frac{w_3}{w_0}]$$

IV. Results and Discussion

A. Concrete Pavement Analysis

Deflections in a squire plate supported by dense liquid foundation caused by interior load were calculated using the JSLAB and ILLISLAB computer programs [15], along with Westergaard and Pickett closed-form formula in this case study. The developed FEM also list the results that are summarized in Fig. 1. Apparently, slab sizes, number of elements, and shape of elements affect the deflection results. The purpose of this analysis is to verify the deflections under HWD load, therefore these factors are not in the scope of this study.

Modulus of slab is 27,579 MPa (4,000,000 psi), the assumed modulus of subgard reaction is 54.2 MPa/m (200 pci), and Slab Poisson's ratios 0.15, the known concrete pavement thicknesses 254 mm (10 in.) are then put into FEM to predict center deflections. The loaded area was assumed to be a square of 254 mm x 254 mm (10. in. x 10. in.), therefore the applied pressure was 689. kPa (100 psi) at the center of slab. Center deflections were considered for both the ILLISLAB and JSLAB computer Deflection results was listed [15].

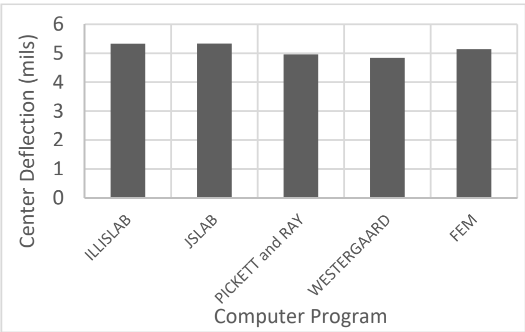

Fig. 1 Deflection comparison under interior load

B. NAPTF F/HWD Round-Up Concrete Testing Site

The F/HWD Round-Up pavement section was constructed at Federal Administration (FAA) NAPTF, which is located at William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. Rigid test pavement and subgrade were constructed on medium strength subgrade with a CBR value approximately 5-6. The rigid pavement includes 406 mm (16 inch) P-501 PCC surface layer, 152 mm (6 inch) P-306 Econocrete base layer, and 1422 mm (56 inch) Dupont Clay subgrade layers. The subgrade was constructed in control lifts of approximately 203 mm (8 inch) to the depth of 1981 mm (78 inch), the slab size is 4500 mm by 4500 mm (15 feet by 15 feet).

FEM calculation results from the PCC slab 4500 mm by 4500 mm (15 feet by 15 feet) at this F/HWD Round up site are shown in Fig. 2. The radius of relative stiffness is the function of AREA, as expected. However, the modulus of concrete did not affect this curve significantly, which means that the AREA and radius of relative stiffness can be used as a parameter to backcalculate the pavement materials [5]. It also indicates that the slab modulus is not sensitive in backcalculation because 35 GPa (5,000,000 psi) has a very similar curve to the concrete pavement modulus of 21 GPa (3,000,000 psi), it may cause the errors of estimating the pavement modulus.

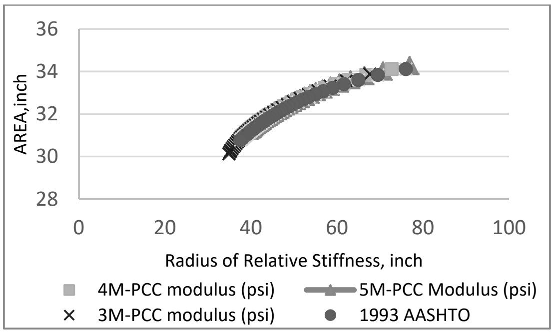

Fig. 2 Relationship between RRS and AREA

Fig. 3 summarizes the relative difference between the finite slab and the infinite slab (Westgaard), it is found that with the same AREA, the Westgaard solution generated a relative higher radius of relative stiffness, by definition in (1); it means that the relative higher elastic modulus could be obtained. In addition, the figures show the slab size does affect the backcalculation results with the increase of the AREA. Using the Westgaard solution with the assumption that the infinite slab may be acceptable for the engineering practices, but with higher value of AREA, it can cause some estimation error in both slab modulus and modulus of subgrade reaction.

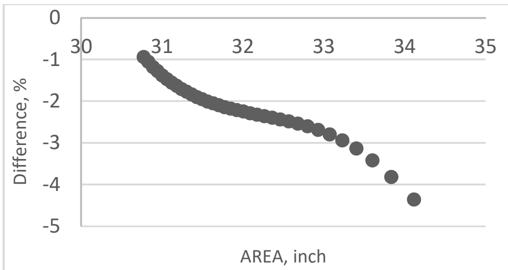

Fig. 3 Relative difference between infinite slab and limited slab

C. Nondestructive Tests

NDTs were performed at different times using FWD and HWD equipment. Tests were performed at 53.33 kN (12,000 lbs) and 106.67 KN (24,000 lbs), and 160.00 KN (36,000 lbs). At 30.5 cm (12 inch) segmented load plates were used during this test sequence and the response was measured with seven load plates, which were used during this test sequence, responses were measured with seven seismometers spaced at 12 inches each. The FWD data were used in the backcalculation program FEMBAK and 1993 AASHTO to determine layer material properties. Before each drop of the falling weight, seven sensors were lowered and placed on the pavement surface so that the surface deflection could be measured during each drop. The deflections were measured at 0, 305, 609, 904, 1209, 1514, and 1819 mm (0, 12, 24, 36, 48, 60 and 72 inches) away from the center of the loaded area. Variation characteristics of deflection data of the first four sensors are listed in Figs. 4 and 5. It was found that the COV of deflections at different sensor increase with the distance to the loading plate. Therefore, the variation of this deflection can affect the backcalculation results significantly.

In the process of backcalculating pavement layer moduli, the accuracy of the final backcalculated moduli is affected by the tolerance allowed within the procedure for determining a match between the calculated and measured HWD deflections. the measure of how well the calculated deflection basin matches the measured deflection basin is described as the "error check", or "goodness of fit". ASTM D5858-96, Standard Guide for Calculating In-Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory modulus, recommends to use a root mean square (RMSE) percent error, it defined as follows:

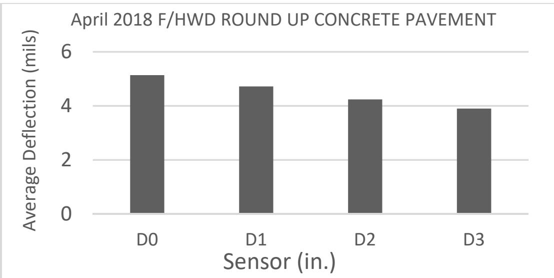

Fig. 4 Average deflection at different sensors (normalized to 160 kN (36,000 lb))

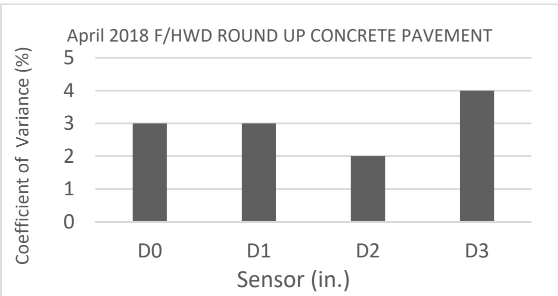

Fig. 5 Deflection variations at different sensors (normalized to 160 kN(36,000 lb))

$$RMSE = \sqrt{\sum_{i=1}^{4} \frac{1}{4}\left(\frac{w_i^c - w_i^m}{w_i^m}\right)^2} \times 100 \quad (10)$$

where w_i^c =calculated pavement surface deflection at sensor *i*, and w_i^m =measured pavement surface deflection at sensor *i.*

ASTM recommends a maximum tolerance limit of RMSE is 1 to 2%; for the total of 33 HWD testing spots in this test track, the average of Root Mean Square (RMS) is 2%. The proposed approach is efficient and accurate.

D.Subgrade Soil Tri-Axial and Plate Load Test and Backcalculated Results

There are a variety of methods can be used to determine layer resilient moduli. Laboratory testing procedures are normally followed to obtain the most accurate results. The plate load tests were used to measure the modulus of subgrade reaction for in situ subgrade material. The test involves pressing a steel bearing plate into the surface to be measured with a hydraulic jack. The resulting surface deflection is read from dial micrometers near the plate edge and the modulus of subgrade reaction is determined. The FAA [1] offers the following relationship between k-values from a plate bearing test and resilient modulus (M_R):

$$E = 20.15K^{1.284} \quad (11)$$

where E = Elastic modulus of subgrade (psi), k = modulus of subgrade reaction (pci).

Alternatively, a direct measurement method would be ideal for determining in situ moduli and then use backcalculation techniques to calculate resilient modulus from field measurements. The FWD experimental data are generally summarized as a deflection basin that is constructed from the peak deflections recorded at each of the measurement locations. The stiffness of the various material layers in the pavement system is calculated from these deflection basins through a process called backcalculation. The Econocrete P-306 can be a obtained by Reference [16]. There are big discrepancies between laboratory tested modulus and backcalculated modulus. The reason could be due to the different situations when testing.

Table I summarizes the various moduli from different methodology at the concrete pavement section of F/HWD Round-Up. The deflection field data were collected on April 17, 2018. The study herein discovered that the reduction factor of 2 suggested when considering the compatibility between backcalculated composite base and subgrade modulus and plate loading test k-value for subgrade layer. The concrete pavement of the F/HWD Round up shows that the COV of subgrade ranged between 18% and 35%. This observation is most likely caused by several factors such as construction, materials, and moisture, and so forth. Apparently, using the composite modulus value of material characterization as an input of pavement design will provide thinner thickness as well as some risk in the pavement thickness design. The FAA's concrete pavement design methods require subgrade strength as a design input; the concrete surface layer flexural strength can be treated as either a default value of 4.49 GPa (650 psi) of standard FAA P-501 concrete materials or a value as concrete materials. Considering both lab and backcalculation results, the fixed concrete P-501 surface layer modulus of 28 GPa (4,000,000 psi) in FAARFIELD is considered as a conservative design.

TABLE I
MEAN AND STANDARD DEVIATION FROM BACKCALCULATED MODULUS

Layer Modulus	FEMBACK (ksi)		1993 AASHTO (ksi)		Lab Test (psi)		PLT (pci)
	Mean	St Dev	Mean	St Dev	Mean	St Dev	Mean
P-501	6,897	1,356 (19%)	4,579	1,029 (22%)	707*	52 (7%)	N/A
P-306	1,936	594 (20%)	1029866	257 (22%)	525**	204 (38%)	N/A
P-152***	201	37 (18%)	240	85 (35%)	8,210	1,655 (20%)	110

Note: *28-Day Flexural Strength; **7-Day Compressive Strength; ***P-152 unit is pci; PLT: Plate Loading Test; P-501: concrete surface; P-306: Econcrete base; P-152: Subgrade; 1kpa=6.9 MPa.

V. CONCLUSION AND RECOMMENDATIONS

Based on the analysis, the following conclusions can be drawn:

- The deviation of each layer is different at F/HWD Round-Up rigid pavement testing section, in which rigid pavement can be as high as 20%, and subgrade can be as high as 35% depending different test methodology.
- Different backcalculation approaches can generate significantly different modulus; therefore backcalculation should be in cooperation with lab testing results in pavement design in order to obtain rational design inputs.
- The proposed procedure is capable of predicting concrete, base layer and subgrade material modulus and therefore provides an alternative for pavement evaluation.

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