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16. Abstract

RMODS is a rigid pavement evaluation and backcalculation system developed by the Texas Transportation Institute for the Texas Department of Transportation. The system processes Falling Weight Deflectometer data to generate information on the structural strength of the concrete slab and the subsurface support. Outputs from the system include:

a. the elastic modulus of each layer,
b. the modulus of subgrade reaction (k) and characteristic length (l_k) for center slab or edge loading,
c. the load transfer efficiency of joints or cracks, and
d. the presence of voids beneath joints.

This report provides the technical background to RMODS. The backcalculation models included are the Hertz and linear elastic models for processing center slab deflection data and the Westergaard model for processing free edge deflection data. The void detection procedures included both the methods proposed by the Center for Transportation Research (CTR) and the National Cooperative Highway Research Program (NCHRP).

Case studies conducted on several in-service concrete pavements are also included.

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RIGID PAVEMENT EVALUATION SYSTEM:

IMPLEMENTATION OF RMODS

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Research Study Title: Rigid Pavement Evaluation System

Sponsored by
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IMPLEMENTATION RECOMMENDATIONS

In order to implement this system, the following are recommended:

1. It is recommended that FWD data be collected on several upcoming new concrete pavement design and rehabilitation projects and that RMODS be used to process the data. The backcalculated values, particularly k values, should be compared with those obtained with traditional methods.
2. On upcoming underseal projects the Load Transfer Efficiency and Void Detection procedures should be used to predict the presence of voids. Joints with no voids should not be undersealed. Validation of the predictions can be made with the Epoxy Core Test.

DISCLAIMER

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LIST OF ABBREVIATIONS AND SYMBOLS

RMODS	-	Rigid Pavement Modulus computer program for backcalculating layer properties
TxDOT	-	Texas Department of Transportation
TTI	-	Texas Transportation Institute
JCP	-	Jointed Concrete Pavement
CRCP	-	Continuously Reinforced Concrete Pavement
E_1 or E_c	-	Elastic modulus of concrete
E_2, E_3..	-	Elastic modulus of layers beneath the concrete layer
E_{sg}	-	Elastic modulus of subgrade
k	-	Modulus of subgrade reaction
l_k	-	Radius of relative stiffness
p	-	Applied uniform pressure
a	-	Radius of loading plate (circular plate)
h	-	Thickness of the slab
ν_c	-	Poisson's ratio of the concrete
D	-	Stiffness of the slab
W1..W7	-	Falling Weight Deflectometer sensor deflections in mils

SUMMARY

RMODS is a rigid pavement evaluation and backcalculation system developed by the Texas Transportation Institute for the Texas Department of Transportation. The system processes Falling Weight Deflectometer data to generate information on the structural strength of the concrete slab and the subsurface support. Outputs from the system include:

a. the elastic modulus of each layer,
b. the modulus of subgrade reaction (k) and characteristic length (l_k) for center slab or edge loading,
c. the load transfer efficiency of joints or cracks, and
d. the presence of voids beneath joints.

This report provides the technical background to RMODS and includes the following backcalculation models: the Hertz and linear elastic models for processing center slab deflection data and the Westergaard model for processing free edge deflection data. The void detection procedures included both the methods proposed by the Center for Transportation Research (CTR) and the National Cooperative Highway Research Program (NCHRP).

This report also includes case studies conducted on several in-service concrete pavements.

CHAPTER 1. INTRODUCTION

This version of Rigid Modulus (RMODS) is capable of analyzing raw Falling Weight Deflectometer data collected on rigid pavements and can perform the following tasks:

- Analyze load transfer capability of joints and/or cracks using different schemes.
- Run the backcalculation schemes using Hertz and Layered Elastic system theories for center deflections and Westergaard theory for edge deflections.
- Detect loss of support or voids underneath working joints and/or cracks of jointed concrete pavements (JCP).
- Output the results in tabular and graphical form to the screen and/or to a printer.

The objective of this technical report is to present an overview of RMODS and the theory behind each of the rigid pavement evaluation procedures. The rigid pavement evaluation parameters are pavement layer properties, void detection and load transfer efficiency of joints. A case study on the implementation of RMODS is presented with the FWD data collected from IH10 (Beaumont), and US52 (Lexington, NC). These specific projects have been selected for the case study to investigate layer properties and suspected loss of load carrying capacity of the pavements. Where possible, limited field verification tests were conducted on the void predictions.

Figure 1 shows an overview of the RMODS program; it consists of an FWD data conversion module, a load transfer efficiency/void detection module, and a layer backcalculation module. The FWD data conversion module reduces the field deflection data according to user specified option(s) and creates a data output file that RMODS can readily process by RMODS. While processing the field FWD file with RMODS, the user needs to input the location and sequence of the data collection by responding to simple pop-up screens. A detailed explanation of the RMODS operation is included in the user manual, TTI Report 1939-2. The subsequent chapters explain in detail the load transfer/void detection and the layer properties backcalculation modules.

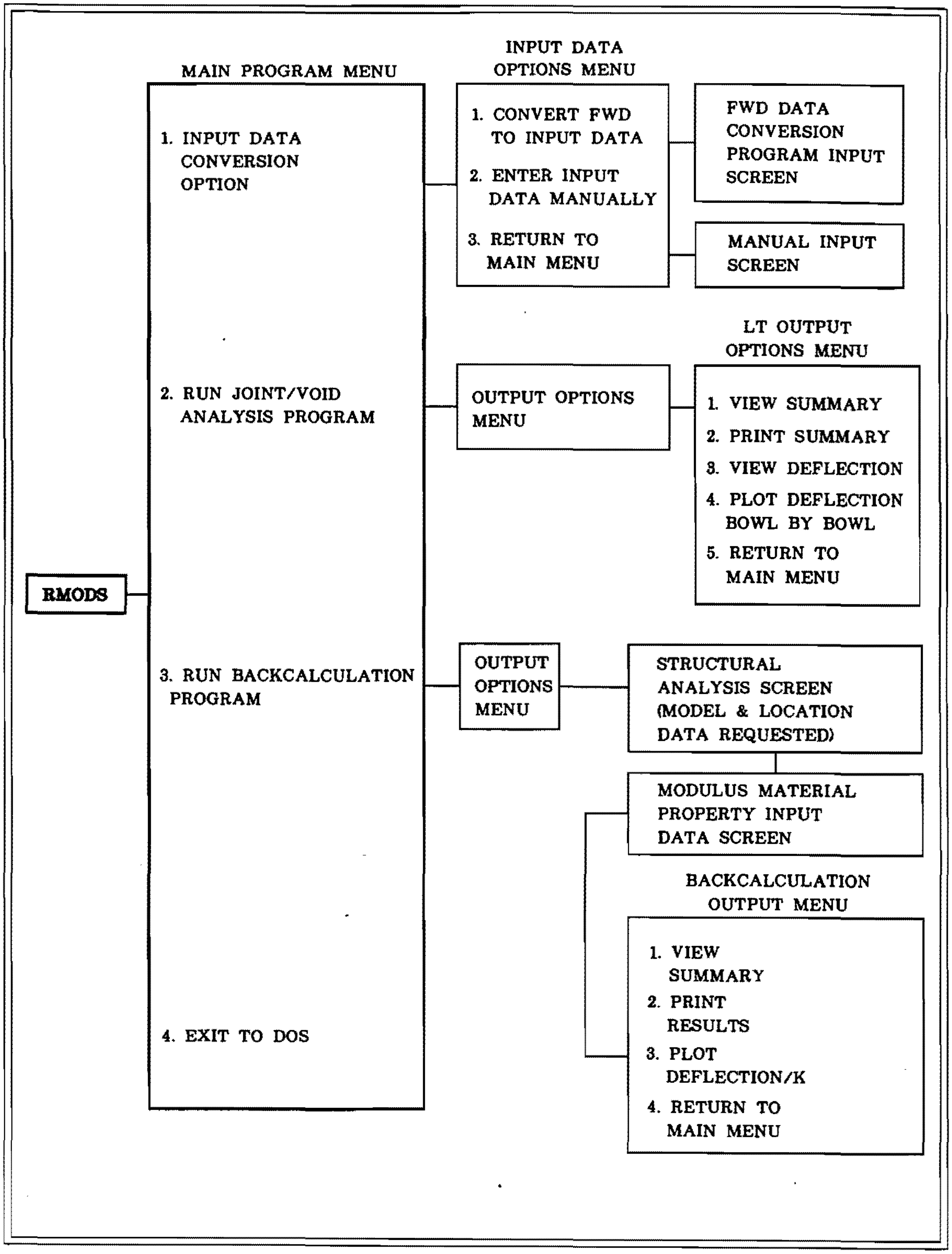

Figure 1. RMODS Overview.

CHAPTER 2

RIGID PAVEMENT EVALUATION PARAMETERS - RMODS

The various rigid pavement evaluation features incorporated in the RODS computer program are:

a. Backcalculation of layer properties:
   - Elastic modulus of concrete (E_1 or E_c) and layers beneath (E_2 ,E_3 ...E_{sg}), and
   - Modulus of subgrade reaction (k);

b. Load transfer efficiency of joint/cracks using different schemes; and

c. Void detection under joints/cracks at corner location.

The following three sections of this report will present the background to each of these areas.

2.1 BACKCALCULATION OF LAYER PROPERTIES

2.1.1 Introduction

All backcalculation schemes are based on the pattern search technique for matching the measured deflection bowl with a theoretically calculated deflection bowl. The set of moduli that gives the best fit between the measured and calculated deflection bowls is chosen to represent the pavement parameters. The procedure for evaluating the pavement parameters is similar to the one developed in MODULUS 4.2. It includes the following modules (each module will be dealt separately in detail):

a. In the case of the multilayer system, the depth of the bedrock is evaluated at each station and load level. An average depth is selected for the final evaluation of the pavement parameters.

b. The pattern search technique is used to backcalculate the pavement parameters for each of the specified models. Since the procedure is based on a large number of calls to the theoretical model, these calls were replaced by the generation of a database and the Lagrange interpolation technique.

In the case of Hertz and Westergaard theories, the program checks whether the required database exists or not. The database is defined by:

1. the radius of the loading plate;
2. the position of the sensors with respect to the loading plate, and
3. in the case of edge loading, the distance from the plate rim to the free edge.

The program will generate the required database if it does not exist.

In the case of the multilayer system, the program will generate a database for the specific input layer thicknesses, computed depth of bedrock, and ranges of specified moduli, using the same procedure as available in MODULUS 4.2.

c. RMODS analyzes every deflection bowl with the corresponding theoretical model. For example, the edge deflection bowls are analyzed using only the Westergaard model, since all other models are not applicable. The center slab deflection bowls are analyzed with either the Hertz on the multilayer elastic models.

This chapter presents the background of the different models and the procedures for generating databases and backcalculating the pavement parameters.

2.1.2 Description of The Theoretical Models

The models can be separated into different categories, based on the underlying assumptions concerning:

i. the representation of the concrete upper layer;
ii. the size of the layer, whether infinite, semi-infinite or finite; and
iii. the constitutive law for representing the materials underneath the concrete.

It is worth emphasizing that all of the theories implemented in the RMODS are linear; they do not include any nonlinear material property or discontinuity between layers.

In one case, the concrete upper layer is assumed to behave like a thin plate (or slab). This assumption is included in the Hertz and Westergaard models and leads to the following consequences:

a. the effect of the vertical stresses in the layer is neglected;
b. the stress distribution due to bending across the thickness is linear; and
c. only the vertical deformations of the slab (at its plane of symmetry) and of the layer underneath are compatible.

In the case of the multilayer elastic system, all stresses and deformations are taken into account, i.e. no stresses or deformations are neglected.

The extent (size in the horizontal direction) of the upper layer of the slab is a topic that is very difficult to deal with. Only numerical methods such as Finite Elements, Boundary Elements and Finite Differences methods can handle finite plates or layers. The Hertz model and the multilayer elastic model assume that the slab or layer extends to infinity in both x- and y-directions. Practically, this assumption implies that the size of the plate must be large, and the load and measuring devices (sensors) are located far from any crack or joint. The Westergaard model assumes that the slab is semi-infinite, i.e. it includes a free edge. No other discontinuity can be included. Practically, this assumption implies that a free edge condition exits, far from any other crack or joint.

Basically, two constitutive laws are used to characterize the materials underneath the upper layer or slab:

a. the Hertz and Westergaard theories assume the Winkler model composed of linear vertical springs (or of a liquid), and
b. the multilayer elastic layered theory assumes the Hooke's model of a linear elastic continuous material.

These two constitutive models are different, and it is difficult to relate one to the other.

In the light of the above discussion, the description of the three models used by RMODS is summarized in Table 1:

a. The Hertz model refers to an infinite plate resting on a Winkler subgrade model;
b. The Westergaard model refers to a semi-infinite plate resting on a Winkler subgrade model; and
c. The multilayer elastic model refers to several layers (up to four in the program) made of a linear elastic material.

Table 1. Description of Rigid Pavement Layer Backcalculation Models.

Model	Hertz	Westergaard	Multilayer
Upper layer	Infinite slab	Semi-infinite slab	Infinite layer
Subgrade model	Winkler	Winkler	Hooke
Loading condition	Center	Free edge	Center
Basic model parameters*	l_k and k or E_c and k	l_k and k or E_c and k	E_1,E_2....E_4

* see definition in Notation and following paragraphs.

2.1.3 Generation of the Databases

The generation of the databases requires the use of numerical integration procedures for the Hertz and Westergaard models and of an existing computer code WESLEA (Van Cauwelaert, 1989) for the multilayer system (also based on numerical integration). The following paragraphs give details of the integrated equations and the integration process.

Hertz Model

The deflection of the slab at any distance r from the center of a loading circular area is given by

$$w(r) = \frac{pa^4}{D} \int_0^{\infty} \frac{J_1(x)\ J_0(xr/a)}{x^4 + (a/l_k)^4} dx \ ,$$

where:

p = applied uniform pressure,

a = radius of loading plate (circular plate),

$D = E_c h^3 / 12 (1-\nu_c^2)$ = stiffness of the slab,

E_c = modulus of the concrete,

h = thickness of the slab,

ν_c = Poisson's ratio of the concrete,

r = radial distance from center of the loading plate,

l_k = characteristic length ($l_k^4 = D/k$),

k = modulus of subgrade reaction (spring constant),

x = variable of integration, and

J_0, J_1 = Bessel functions.

The integration of the above equation is made using the Gauss quadrature between values of x corresponding to the zeroes of the Bessel functions. The computer program used for the integration is listed in Sevadurai (1979). The accuracy obtained was increased by increasing the number of intervals between two consecutive zeroes of the Bessel functions and by extending the integration limit.

The generation of the theoretical database includes computation of the deflections for the specified radius a at the specified radial distances (r of the sensors) from the load and 17 values of l_k from 250 to 3500 mm (10 to 140 inches). The data is stored in the file HERTZOUT.DAT for use in the backcalculation procedure. As mentioned previously, the program compares the user inputs of plate radios and sensor spacings with those used to generate the default database. If there is not a match, a new database will be generated.

Westergaard Model

The deflection of the slab at any distance x from the center of loading circular area along a free edge is computed in two steps (double integration). In the first step, the deflection caused by a point load is computed at 9 distances (representing 3*3=9 positions in the x-y plane) from the concentrated load. In the second step, a numerical integration of the deflection caused by a point load is performed over the circular area to give the deflection at any distance caused by a uniform pressure over a circular area. In the course of the second step, the Lagrange interpolation scheme is used to interpolate the results from the first step to evaluate the deflection caused by a point load at any specified position (within the range of the nine positions).

The deflection at any distance from a point load is given by

$$w_{II}(r)=\frac{2P}{\pi k l_k^2}\int_0^{\infty}\frac{\gamma\cos\frac{\alpha x}{l_k}\left(A\cos\frac{\beta y}{l_k}+B\sin\frac{\beta y}{l_k}\right)e^{-\gamma y/l_k}}{1+4(1-\nu)\alpha^2\gamma^2-(1-\nu)^2\alpha^4}d\alpha$$

$$w_I(r)=w^1_{II}+\frac{P}{\pi k l_k^2}\int_0^{\infty}\frac{\cos\frac{\alpha x}{l_k}}{\beta^2+\gamma^2}\left(\beta\cos\frac{\beta y}{l_k}\sinh\frac{\beta y}{l_k}-\gamma\sin\frac{\beta y}{l_k}\cosh\frac{\gamma y}{l_k}\right)d\alpha$$

$$\beta = \sqrt{\frac{\sqrt{1+\alpha^4}-\alpha^2}{2}}$$

$$\gamma = \sqrt{\frac{\sqrt{1+\alpha^4}+\alpha^2}{2}}$$

$$A = \frac{1}{2}\{1+2\gamma^2 g-(1-\nu)^2\alpha^4+[1+(1-\nu)^2\alpha^4+g\sin\frac{2\beta c}{l_k}-2\gamma^2 g\cos\frac{2\beta c}{l_k}]e^{-2\gamma c/l_k}\}$$

$$B = \frac{1}{2}[2(1-\nu)\alpha^2-g+(2\gamma^2 g\sin\frac{2\beta c}{l_k}+g\cos\frac{2\beta c}{l_k})e^{-2\gamma c/l_k}]$$

$$g = \frac{\nu\alpha^2}{2(\gamma^2+\beta^2)}[2\gamma^2-(1-\nu)\alpha^2]+\frac{3(1-\nu)\alpha^2}{2}-\gamma^2 \ ,$$

where:

ν = ν_c = Poisson's ratio of the concrete,

l_k = characteristic length ($l_k{}^4$= D/k),

c = distance from x-axis to the edge of the slab, and

x, y = rectangular coordinates (x-axis is along the free edge, y-axis perpendicular to the free edge: x = 0 and y = 0 correspond to the position of the point load).

The integral is evaluated using the Gauss integration technique. A set of 3 by 3 positions are generated for use in the integration of the point load result over the loading area.

In the second step, the contact area is subdivided into surface elements with given pressure magnitudes at the nodal points. Figure 2 shows the upper right quarter of a circular area subdivided into isoparametric elements with 4 nodes. The integration over the surface elements carried out using the 4x4 Gauss quadrature scheme (Uzan and Sides, 1987), i.e.:

$$w=\sum_m w_m = p\sum_m \left[a_m\left(\sum_{j=1}^{4}\sum_{k=1}^{4} r_j r_k w_{jk}\right)\right] ,$$

where:

w = deflection at point (x,y) due to a uniform pressure distribution over the contact circular area,

w_m = deflection at point (x,y) due to a uniform pressure distribution over element m,

w_{jk} = deflection at point (x,y) due to a unit force (point load) applied at the Gauss integration point ((x_j,y_k) obtained by Lagrange interpolation of the results from step one),

a_m = area of element m, and

r_j,r_k = Gauss weighing factors corresponding to the point of integration ($_j$x $_k$, y) inside element m.

The database is generated for 17 values of l_k ranging from 250 to 3500 mm (10 to 140 inches), for the specific distance from the edge of the loading plate to the free edge of the pavement, for the specific radius (a) of the plate, and for the given positions of the sensors. In the present version of the system, the distance of the loading plate rim from the free edge is assumed to be 12.5 mm, corresponding to field positioning of the plate rim between zero and 25 mm from the edge. The theoretical deflection bowls generated using the Westergaard model are stored in the file WESTOUT.DAT for use in the backcalculation.

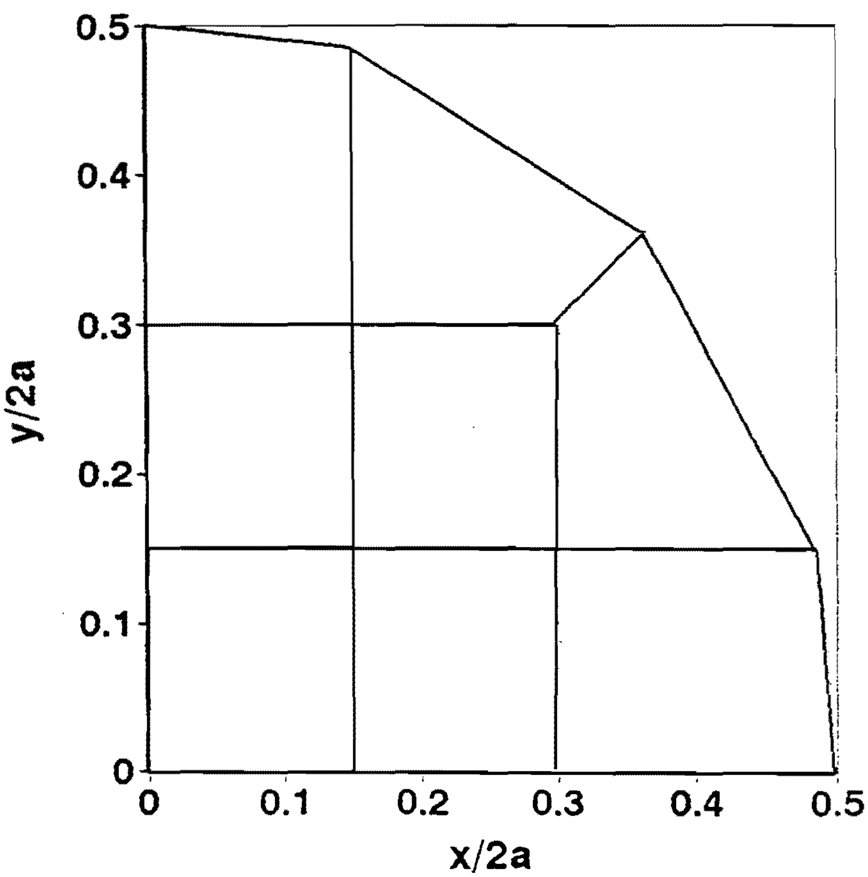

Figure 2. Illustration of Isoparametic Elements Used to Generate Surface Pressure Distribution in Westergaard Model (Uzan and Sides, 1987).

As mentioned previously, the program checks whether the required database exists or not, and a new database is generated if necessary.

Multilayer System Model

The multilayer system operates in a way similar to the MODULUS 4.2 computer code for flexible pavements. It uses the computer code WESLEA for generating the required databases for the specific radius of contact area, radial distances of the sensors, and layer thicknesses including the subgrade thickness.

2.2 LOAD TRANSFER EFFICIENCY

To evaluate the load transfer efficiency of the joints, two procedures have been incorporated into RMODS. These methods and the sources are:

1. CTR Method	Methodology outlined in CTR Report 387-3F, and
2. J. Uzan Method	Texas Transportation Institute.

In order to evaluate the load transfer efficiency using RMODS, FWD data must be collected in a specific format. Figure 3 shows the required FWD sensor configuration. RMODS cannot evaluate LTE without FWD deflections at the -12 sensor spacing location. Each of the different LTE methods incorporated in RMODS is briefly explained below.

2.2.1 CTR Method

The original method uses FWD deflections measured at both upstream and downstream locations of joints and cracks (refer to Figure 4). Figure 4 shows the placement of the sensors and the locations of load application points. This version of RMODS has been programmed to process only the downstream deflection data shown in position 3B of Figure 4. The decision to collect only downstream data was based on field expediency. It is expensive, time consuming and sometimes dangerous to collect FWD data on concrete pavements. The benefits of upstream data were judged not to outweigh the costs.

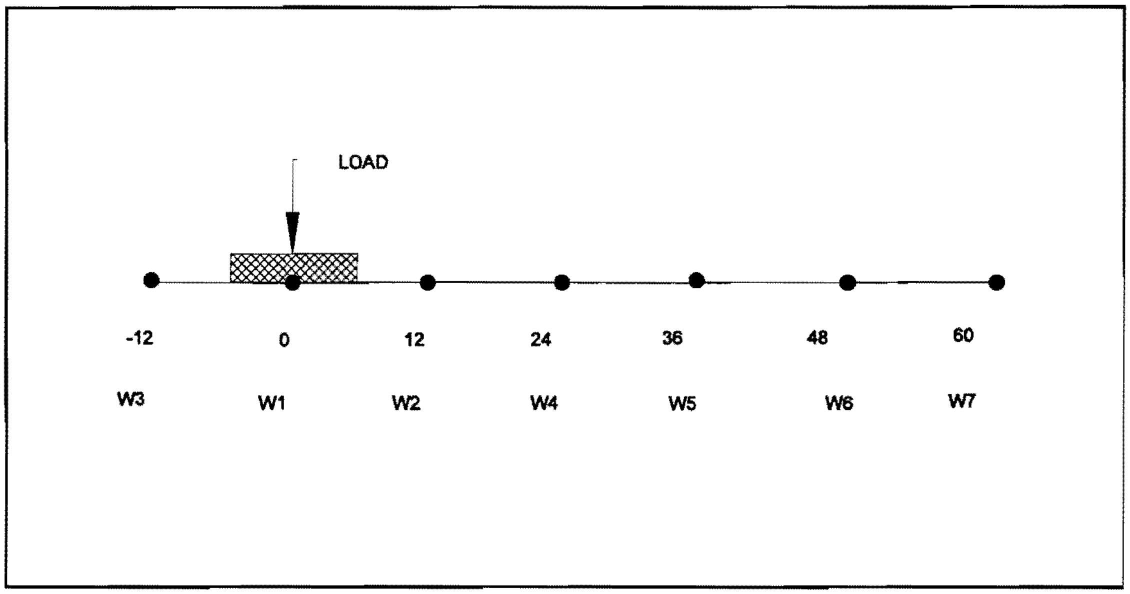

Figure 3. Falling Weight Deflectometer Sensor Configuration for Load Transfer Efficiency Evaluation. The Joint is Positioned Midway Between W_1 and W_3.

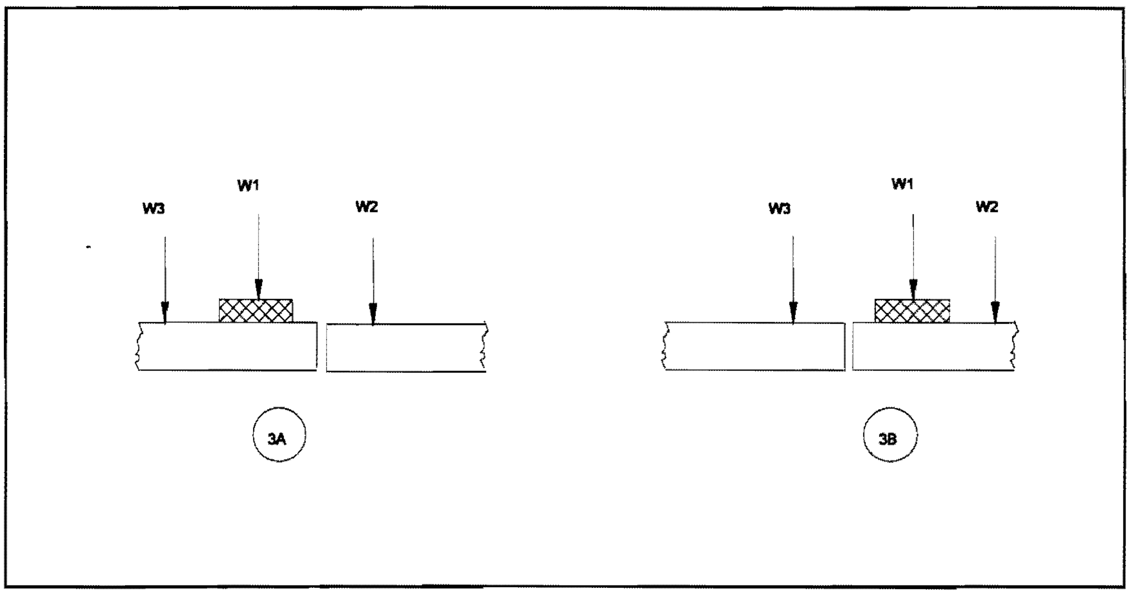

Figure 4. FWD Data Collection Procedure to Evaluate LTE Using CTR Method.

UDR (Upstream deflection ratio) and DDR (Downstream deflection ratio) are defined as follows.

UDR = smallest of W_2/W_3 or W_3/W_2

DDR = smallest of W_2/W_3 or W_3/W_2

RMODS calculates the Downstream Deflection Ratio from the position 3B in Figure 4. In the CTR study the average of downstream and upstream ratios were used to classify the load transfer. Ratios greater than 0.9 were classified as "Full Load Transfer," below 0.2 was "No Load Transfer."

2.2.2 Uzan Method

In this method, only downstream deflection bowl data is needed to determine LTE. The ratio u is given by W_3 divided W_1 and calculated for the FWD deflections collected from downstream joint or crack. This simple Load Transfer Efficiency is normalized based on the W_2/W_1 ratio measured at center slab. If center slab deflection data is not available, then the ratio m is set at 0.95. It is to be noted that previously obtained values of m can be used in calculations until additional center slab data are obtained. LTE is given by the ratio of u/m. It is expressed in percentages from 0% to a maximum of 100%. RMODS utilizes the following expressions to determine LTE by the Uzan Method.

$$LTE\ (\%) = 100 * (U/M),$$

where:

$U = W_3/W_1$ (Upstream deflection),

$m = W_2/W_1$ (If Center Slab Deflections are available), and

$m = 0.95$ (If Center Slab deflections are not available).

2.3 VOID DETECTION

2.3.1 Introduction

The unsupported area beneath the concrete slab surface which is caused by the combination of excess moisture, pumping of fines, and erosion is defined as voids. In general, voids are created near transverse joints, working cracks, and edges (Corvetti and Darter). Due to the presence of voids, the rehabilitation of pavements will not serve the intended enhancement of pavement life. Hence, prior to any overlay rehabilitation, support has to be restored by filling the voids with grout. Experimental projects on grout subsealing in Illinois revealed that the high intensity pressure grouting without confirmed knowledge of voids could prove disastrous, in which case the slab might be lifted due to the excessive pressure. This introduces the significance of void detection. The following paragraphs include a brief overview on void detection procedures and their subsequent incorporation in the RMODS computer program.

Figure 5 shows a schematic diagram of void creation. In general, voids are created by a combination of moisture and pumping due to poor load transfer efficiency of crack and joints. Also, previous observations indicate that voids are mostly created beneath the leave side of the slab.

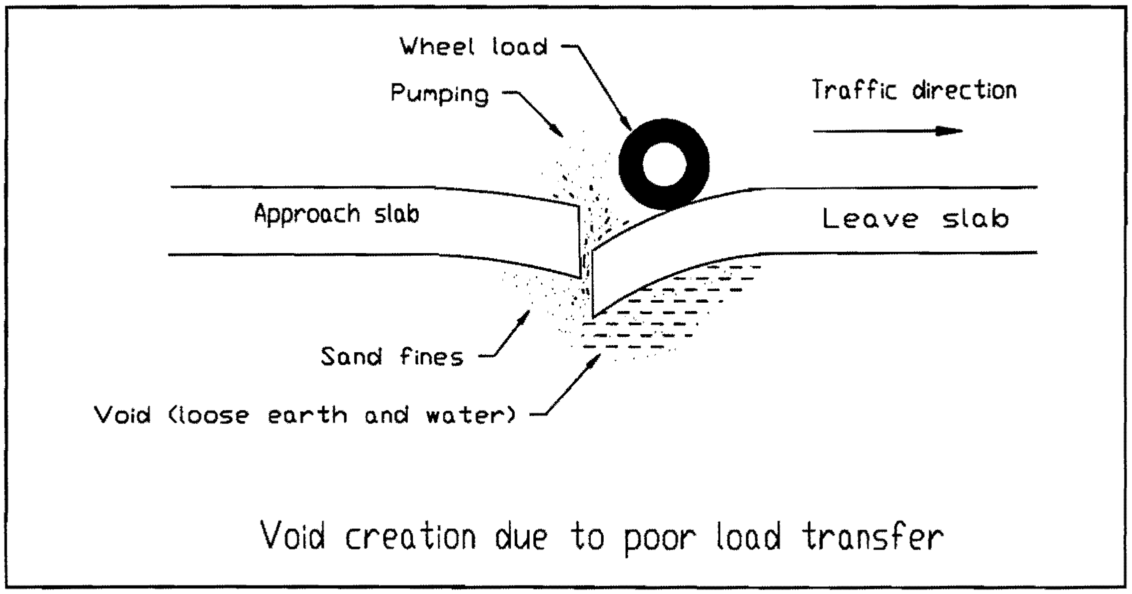

Figure 5. Schematic Describing the Creation of Voids under Jointed Concrete Pavement.

A literature search conducted in this study identified several void detection methods that utilize Falling Weight Deflectometer data. All these void detection methods are empirical in nature. To accomplish the task of selecting the best void detection procedure, tests were conducted at the Texas Transportation Institute on slabs with artificially created voids. Based on the success rate of each method, two void detection methods were selected for inclusion in RODS: the CTR Method (Ricci, et al. 1985) and the NCHRP Method

(Crovetti and Darter, 1985). These two methods are incorporated in the RMODS computer program. Note that both procedures were capable of processing both upstream and downstream deflection data; however, in RMODS it is proposed that only the downstream data be collected. The downstream location as shown in Figure 5 is where voids are usually located. The following paragraphs briefly describe each method and the underlying concepts.

2.3.2 CTR Method

This method was developed by the Center for Transportation Research in Austin and is reported in CTR Report 3-8-84-387-3F. Based on the deflection bowl shape of the FWD data, two mathematical parameters M and Q are defined, which, when empirically correlated, can predict the presence of voids. Figure 6 illustrates the sensor arrangement and exaggerated view of the defection bowl along with the diagrammatic representation of M and Q. The parameter M is the angle between the line joining point of peak deflection and the point of deflection at the first sensor on the leave slab and the vertical, while Q is the angle between the line joining the first sensor of the leave slab and the seventh sensor and the horizontal line. Voids are present if the Q factor is ≥ 22. These factors are given by:

$$Q = Tan^{-1}\left(\frac{(W_2 - W_7)}{24}\right) \text{ and}$$

$$M = Tan^{-1}\left(\frac{6}{(W_1 - W_2)}\right) .$$

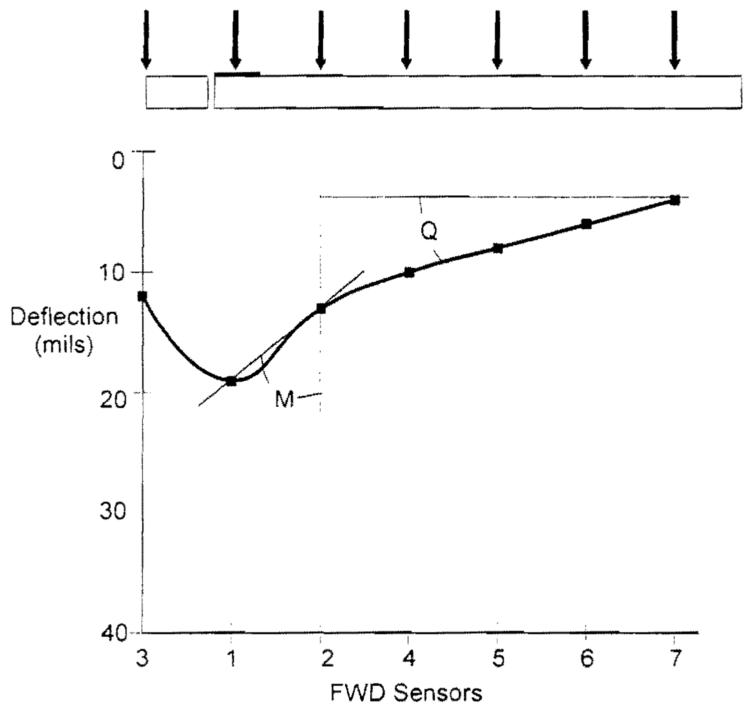

Figure 6. CTR Method of Void Detection.

2.3.3 NCHRP Method

This method of void detection was developed under NCHRP contract 1-21. Of the two methods outlined in the report, the proposed rapid void detection method was adopted for incorporation in RMODS. The procedure involves graphing FWD load versus maximum deflection (mils) and extrapolating a regression line through the data points to intersect the x-axis. If the x-intercept is greater than 2 mils, then voids are present under the slab. Figure 7 illustrates the NCHRP rapid void detection method.

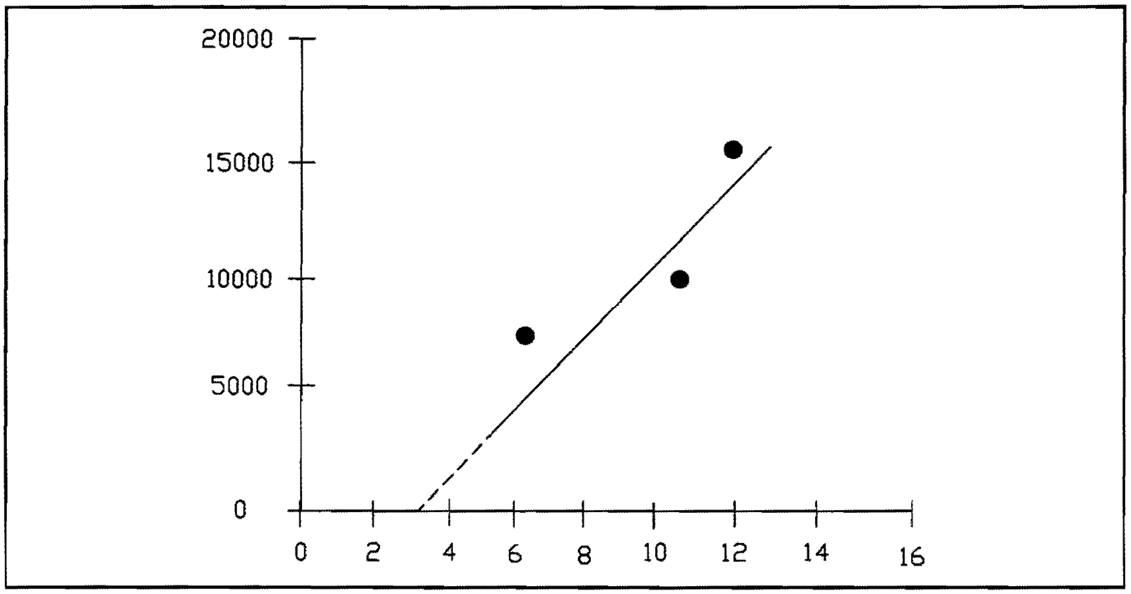

Figure 7. NCHRP Method of Void Detection. (FWD Load vs. Max Deflection)

CHAPTER 3
CASE STUDY AND RMODS IMPLEMENTATION

3.1 CASE A: IH10 BEAUMONT, TX - CENTER SLAB DEFLECTION DATA ANALYSIS

Interstate Highway 10 is one of the several in-service pavements selected for pilot testing of the RMODS computer program. IH10 is rigid pavement consisting of a 250 mm concrete slab over a 150 mm cement treated base on the existing subgrade. The slabs are 4.5 m in length. An initial visual survey revealed pumping and possible poor support conditions.

Falling Weight Deflectometer deflection data were collected beginning at the location of suspected voids for a distance of 600 ft (182.88 m), covering forty slabs. The initial run of FWD was made to collect the data from the center slab location only. The intended objective of this study was to evaluate the overall structural integrity of the pavement layer structure, specifically the subgrade condition. In this case, the center slab results are presented; in Case B, the joint data is presented.

FWD data was collected at four different load levels. In the backcalculation analysis using RMODS, the deflections at the load level closest to 10,000 lb (4536 kg) were utilized. In all the case studies reported in this document, the initial range of elastic moduli of pavement layers as listed in Table 2 was used. A constant value of 0.15 was used for the Poissons ratio of the concrete.

3.1.1 Results

Tables 3 and 4 list the results obtained from the Hertz theory and the elastic layered theory, respectively. In the Hertz theory calculations, RMODS prints out the elastic modulus of concrete E1, radius of relative stiffness l, and the modulus of subgrade reaction k. The mean values of E1, l, and k are found to be 9605.3 ksi, 53.5 and 121.3 pci, respectively. For each position, both the measured and computed bowls are presented together with the mean error per sensor. The & sign at the end of each line indicates that the solution is not close to the limits set up in the deflection database.

Table 2. Initial Range of Elastic Moduli Values Used in RMODS Analysis.

MATERIAL	ELASTIC MODULUS RANGE (ksi)
Concrete	1500 - 7500
Cement Treated Base	250 - 1200
Lime Treated Base (Unbounded)	30 - 80
Lime Treated Base (Bounded)	30 - 900
Subgrade	5 - 30

Table 4 gives the results from the elastic layered theory. The mean value of concrete modulus is 5893.9 ksi, which is significantly less than the value calculated by the Hertz model. The mean values of E_2 for CTB and subgrade is 64.8 ksi and 20.5 ksi, respectively.

In general, similar trends are observed in the support values from both the layered elastic and Hertz solutions. The low values of k correspond to the low values of subgrade modulus. However, the concrete moduli values are significantly different. The linear elastic results appear more reasonable.

Table 3. Summary of Evaluation Parameters Obtained from Hertz Theory Case A - IH 10 Beaumont, Texas.

Page: 1 TTI RIGID MODULUS BACKCALCULATION ANALYSIS SYSTEM (SUMMARY REPORT) (Version 2.0)

District: 20 County: 181 Highway/Road: IH0010 HERTZ THEORY, CENTER DEFLECTION

Station	*Load Plate* * Location *	Load (lbs)	** Measured/Computed Deflection, (mils): ** W1	W2	W3	W4	W5	W6	W7	Modulus E, Radius of Relative Stiffness l, & Mod. of Subg. Reaction k E1	l	k	Err2	Err/ sens.
0.000	Cent/HERT	11,441	4.37	4.02	3.62	4.09	2.67	2.19	1.74					
			4.37	3.18	3.69	3.18	2.67	2.19	1.76	6981.1	46.4	151.0	.93E-01	.66E+01 &
16.000	Cent/HERT	11,421	4.64	4.29	3.91	4.37	2.88	2.43	2.06					
			4.66	3.42	3.95	3.42	2.88	2.37	1.91	6722.5	47.1	137.6	.94E-01	.76E+01 &
32.000	Cent/HERT	11,377	4.87	4.56	4.15	4.52	3.11	2.61	2.22					
			5.05	3.70	4.28	3.70	3.11	2.56	2.06	6132.3	46.9	127.8	.77E-01	.76E+01 &
48.000	Cent/HERT	11,262	4.58	4.32	3.87	4.30	3.11	2.75	2.51					
			4.49	3.67	4.04	3.67	3.28	2.89	2.51	11942.9	61.9	81.6	.52E-01	.66E+01 &
63.000	Cent/HERT	11,266	4.72	4.40	4.10	4.34	3.26	2.93	2.64					
			4.40	3.85	4.10	3.85	3.56	3.27	2.97	20176.2	79.7	50.2	.71E-01	.92E+01 &
77.000	Cent/HERT	11,338	4.44	4.12	3.79	4.13	2.93	2.56	2.28					
			4.14	3.50	3.79	3.50	3.19	2.87	2.55	16534.7	69.8	70.0	.87E-01	.10E+02 &
93.000	Cent/HERT	11,298	4.20	3.86	3.55	3.88	2.73	2.39	2.16					
			4.20	3.33	3.71	3.33	2.92	2.52	2.15	10638.5	56.5	105.2	.50E-01	.66E+01 &
109.000	Cent/HERT	11,199	4.43	4.13	3.76	4.03	2.82	2.39	2.05					
			4.43	3.38	3.84	3.38	2.91	2.46	2.04	8256.4	51.3	119.6	.61E-01	.61E+01 &
123.000	Cent/HERT	11,282	4.27	3.97	3.59	3.96	2.73	2.33	2.02					
			4.27	3.25	3.69	3.25	2.79	2.35	1.94	8458.2	50.8	127.3	.68E-01	.66E+01 &
139.000	Cent/HERT	11,306	3.93	3.67	3.35	3.65	2.54	2.15	1.82					
			3.73	3.04	3.35	3.04	2.72	2.39	2.07	14118.1	61.4	100.1	.95E-01	.10E+02 &
156.000	Cent/HERT	11,330	4.19	3.93	3.63	3.88	2.85	2.53	1.31					
			4.50	3.01	3.63	3.01	2.41	1.87	1.41	4844.0	39.6	198.9	.21E+00	.15E+02 &
169.000	Cent/HERT	11,302	4.40	4.15	3.90	4.06	3.17	2.85	2.56					
			4.27	3.59	3.90	3.59	3.26	2.92	2.59	15183.4	68.1	71.1	.33E-01	.49E+01 &
184.000	Cent/HERT	11,270	4.67	4.33	4.01	4.31	2.97	2.51	2.13					
			4.69	3.50	4.01	3.50	2.97	2.47	2.02	7044.0	48.6	126.5	.76E-01	.65E+01 &
200.000	Cent/HERT	11,199	4.50	4.17	3.83	4.24	2.84	2.42	2.10					
			4.25	3.49	3.83	3.49	3.13	2.76	2.41	12972.6	62.9	83.0	.11E+00	.11E+02 &
215.000	Cent/HERT	11,207	4.65	4.36	4.01	4.31	3.09	2.68	2.33					
			4.39	3.70	4.01	3.70	3.35	3.01	2.66	14698.8	68.2	68.4	.89E-01	.10E+02 &
230.000	Cent/HERT	11,254	4.40	4.12	3.77	4.06	2.81	2.39	1.25					
			4.73	3.10	3.77	3.10	2.45	1.88	1.39	4322.6	38.4	199.6	.20E+00	.15E+02 &
246.000	Cent/HERT	11,155	4.41	4.16	3.88	4.04	3.08	2.74	1.34					
			4.65	3.31	3.88	3.31	2.75	2.22	1.76	5872.3	44.5	150.6	.22E+00	.15E+02 &
261.000	Cent/HERT	11,179	4.49	4.18	3.82	4.13	2.86	2.38	2.03					
			4.41	3.37	3.82	3.37	2.90	2.45	2.03	8277.4	51.3	119.8	.73E-01	.63E+01 &
275.000	Cent/HERT	11,234	4.31	4.00	3.68	4.02	2.78	2.35	1.98					
			4.31	3.28	3.73	3.28	2.82	2.38	1.97	8405.3	51.0	124.8	.66E-01	.59E+01 &
289.000	Cent/HERT	11,195	4.13	3.82	3.49	3.81	2.63	2.19	1.82					
			4.02	3.08	3.49	3.08	2.66	2.26	1.88	9367.3	52.1	128.2	.76E-01	.69E+01 &
306.000	Cent/HERT	11,266	4.26	3.94	3.57	3.96	2.59	2.14	1.74					
			4.26	3.11	3.60	3.11	2.61	2.14	1.72	7091.9	46.6	151.7	.92E-01	.65E+01 &
320.000	Cent/HERT	11,214	4.20	3.91	3.55	3.95	2.61	2.15	1.75					
			4.17	3.08	3.55	3.08	2.61	2.16	1.75	7619.1	47.9	145.9	.93E-01	.64E+01 &
336.000	Cent/HERT	11,226	4.13	3.83	3.52	3.81	2.59	2.15	1.73					
			3.95	3.18	3.52	3.18	2.82	2.46	2.12	12375.0	59.3	100.7	.14E+00	.12E+02 &
351.000	Cent/HERT	11,274	4.12	3.83	3.51	3.80	2.59	2.14	1.78					
			3.97	3.15	3.51	3.15	2.77	2.40	2.05	11466.3	57.0	109.1	.10E+00	.10E+02 &
368.000	Cent/HERT	11,171	4.35	4.01	3.62	4.02	2.59	2.13	1.74					
			4.07	3.26	3.62	3.26	2.89	2.51	2.15	11575.3	58.4	100.2	.18E+00	.14E+02 &

Table 3. Continued.

382.000	Cent/HERT	11,222	4.02	3.72	3.37	3.74	2.46	2.03	1.69					
			4.02	2.94	3.40	2.94	2.47	2.03	1.63	7563.1	46.8	158.8	.91E-01	.67E+01 &
397.000	Cent/HERT	11,199	4.35	4.05	3.72	3.97	2.69	2.16	1.66					
			4.18	3.35	3.72	3.35	2.97	2.58	2.21	11310.3	58.4	97.7	.21E+00	.14E+02 &
413.000	Cent/HERT	11,222	4.31	4.01	3.74	3.98	2.70	2.19	1.77					
			4.29	3.32	3.74	3.32	2.88	2.45	2.05	9157.9	53.1	115.9	.10E+00	.98E+01 &
427.000	Cent/HERT	11,179	4.31	4.00	3.67	3.99	2.69	2.21	1.75					
			4.14	3.30	3.67	3.30	2.91	2.52	2.15	11049.2	57.5	101.8	.14E+00	.12E+02 &
442.000	Cent/HERT	11,218	3.99	3.71	3.41	3.72	2.54	2.15	1.82					
			3.88	3.04	3.41	3.04	2.66	2.28	1.93	10861.6	55.0	119.3	.76E-01	.79E+01 &
457.000	Cent/HERT	11,147	4.42	4.10	3.70	4.13	2.74	2.23	1.76					
			4.20	3.31	3.70	3.31	2.89	2.49	2.11	10140.1	55.5	107.3	.14E+00	.12E+02 &
473.000	Cent/HERT	11,207	4.30	4.01	3.66	3.97	2.75	2.31	1.91					
			4.15	3.28	3.66	3.28	2.88	2.48	2.11	10567.1	56.1	106.9	.83E-01	.88E+01 &
488.000	Cent/HERT	11,238	4.04	3.75	3.40	3.68	2.41	1.92	1.49					
			4.12	2.90	3.41	2.90	2.39	1.92	1.50	6391.9	43.5	179.3	.97E-01	.69E+01 &
503.000	Cent/HERT	11,191	4.28	3.99	3.65	3.95	2.73	2.28	1.87					
			4.17	3.25	3.65	3.25	2.83	2.42	2.03	9776.2	54.1	114.3	.80E-01	.82E+01 &
520.000	Cent/HERT	11,171	4.28	3.98	3.63	3.93	2.72	2.30	1.93					
			4.28	3.24	3.69	3.24	2.78	2.34	1.92	8170.5	50.3	128.4	.66E-01	.60E+01 &
534.000	Cent/HERT	11,203	4.33	4.02	3.71	3.97	2.78	2.29	1.88					
			4.20	3.33	3.71	3.33	2.92	2.52	2.15	10569.1	56.5	104.1	.90E-01	.94E+01 &
548.000	Cent/HERT	11,052	4.42	4.11	3.64	4.15	2.76	2.29	1.83					
			4.39	3.26	3.74	3.26	2.76	2.29	1.86	7251.6	48.2	135.0	.91E-01	.68E+01 &
564.000	Cent/HERT	11,123	4.49	4.14	3.75	4.21	2.73	2.26	1.84					
			4.49	3.27	3.79	3.27	2.74	2.25	1.81	6610.0	46.4	143.0	.95E-01	.67E+01 &
578.000	Cent/HERT	11,056	4.48	4.08	3.67	4.20	2.61	2.13	1.67					
			4.48	3.17	3.72	3.17	2.62	2.11	1.66	5914.7	44.0	158.7	.11E+00	.71E+01 &
593.000	Cent/HERT	11,159	4.32	4.07	3.72	4.01	2.78	2.31	1.83					
			4.33	3.26	3.72	3.26	2.78	2.33	1.91	7803.5	49.5	131.0	.77E-01	.63E+01 &
Mean:			4.35	4.05	3.70	4.03	2.77	2.34	1.89	9605.3	53.5	121.3		
Std. Dev:			0.20	0.20	0.19	0.20	0.20	0.23	0.31	3366.2	8.5	32.9		
Var Coeff(%):			4.67	4.83	5.08	4.91	7.07	9.67	16.20	35.0	16.0	27.2		

Table 4. Summary of Evaluation Parameters Obtained from Layered Elastic Theory Case A - IH10 Beaumont, Texas.

Page: 1 TTI RIGID MODULUS BACKCALCULATION ANALYSIS SYSTEM (SUMMARY REPORT) (Version 2.0)

District: 20 County: 181 Highway/Road: IH0010 LAYERED THEORY, CENTER DEFLECTION

Station	*Load Plate* * Location *	Load (lbs)	W1	W2	W3	W4	W5	W6	W7	E1	E2	E3	ESG	Err2	Err/ sens.
			**** Measured/Computed Deflection, (mils): ****							Modulus E, of the Pavement Layers					
0.000	Cent/MODU	11,440	4.37	4.02	3.62	4.09	2.67	2.19	1.74						
			4.58	4.16	3.66	3.14	2.65	2.22	1.86	5156.3	25.0		22.5	.63E-01	.60E+01 *
16.000	Cent/MODU	11,420	4.64	4.29	3.91	4.37	2.88	2.43	2.06						
			4.81	4.43	3.94	3.43	2.95	2.51	2.12	5720.9	25.0		19.3	.51E-01	.54E+01 *
32.000	Cent/MODU	11,376	4.87	4.56	4.15	4.52	3.11	2.61	2.22						
			5.06	4.68	4.18	3.66	3.15	2.69	2.29	5661.4	25.0		17.7	.41E-01	.49E+01 *
48.000	Cent/MODU	11,261	4.58	4.32	3.87	4.30	3.11	2.75	2.51						
			4.65	4.37	4.01	3.62	3.22	2.85	2.50	7167.1	469.0		14.8	.29E-01	.42E+01 &
63.000	Cent/MODU	11,265	4.72	4.40	4.10	4.34	3.26	2.93	2.64						
			4.77	4.51	4.16	3.77	3.38	3.00	2.64	7841.0	404.6		13.8	.20E-01	.35E+01 &
77.000	Cent/MODU	11,337	4.44	4.12	3.79	4.13	2.93	2.56	2.28						
			4.51	4.24	3.86	3.45	3.03	2.64	2.29	8114.9	25.0		17.0	.31E-01	.43E+01 *
93.000	Cent/MODU	11,297	4.20	3.86	3.55	3.88	2.73	2.39	2.16						
			4.24	3.98	3.62	3.23	2.84	2.48	2.15	8286.8	79.1		17.8	.33E-01	.45E+01 &
109.000	Cent/MODU	11,198	4.43	4.13	3.76	4.03	2.82	2.39	2.05						
			4.57	4.23	3.80	3.33	2.88	2.46	2.10	6376.0	25.0		19.0	.34E-01	.45E+01 *
123.000	Cent/MODU	11,281	4.27	3.97	3.59	3.96	2.73	2.33	2.02						
			4.39	4.07	3.66	3.22	2.80	2.41	2.06	6660.4	87.9		19.0	.39E-01	.48E+01 &
139.000	Cent/MODU	11,305	3.93	3.67	3.35	3.65	2.54	2.15	1.82						
			4.07	3.77	3.39	2.97	2.57	2.21	1.88	7379.6	25.0		21.4	.38E-01	.47E+01 *
156.000	Cent/MODU	11,329	4.19	3.93	3.63	3.88	2.85	2.53	1.31						
			4.63	4.13	3.54	2.96	2.45	2.01	1.64	4005.4	25.4		25.4	.20E+00	.15E+02 *
169.000	Cent/MODU	11,301	4.40	4.15	3.90	4.06	3.17	2.85	2.56						
			4.47	4.24	3.94	3.60	3.25	2.90	2.58	8999.8	566.7		13.9	.15E-01	.31E+01 *
184.000	Cent/MODU	11,269	4.67	4.33	4.01	4.31	2.97	2.51	2.13						
			4.84	4.48	4.00	3.50	3.02	2.58	2.20	5912.9	25.0		18.3	.40E-01	.48E+01 *
200.000	Cent/MODU	11,198	4.50	4.17	3.83	4.24	2.84	2.42	2.10						
			4.64	4.30	3.85	3.38	2.93	2.51	2.14	6102.5	57.5		18.3	.46E-01	.51E+01 &
215.000	Cent/MODU	11,206	4.65	4.36	4.01	4.31	3.09	2.68	2.33						
			4.77	4.47	4.06	3.61	3.17	2.75	2.37	7220.1	25.0		16.3	.29E-01	.42E+01 *
230.000	Cent/MODU	11,253	4.40	4.12	3.77	4.06	2.81	2.39	1.25						
			4.92	4.31	3.62	2.98	2.41	1.95	1.58	3195.1	26.1		26.1	.21E+00	.15E+02 *
246.000	Cent/MODU	11,154	4.41	4.16	3.88	4.04	3.08	2.74	1.34						
			4.92	4.37	3.73	3.11	2.56	2.09	1.71	3576.8	25.0		24.0	.23E+00	.16E+02 *
261.000	Cent/MODU	11,178	4.49	4.18	3.82	4.13	2.86	2.38	2.03						
			4.66	4.30	3.84	3.36	2.89	2.46	2.09	5970.1	25.0		19.1	.40E-01	.48E+01 *
275.000	Cent/MODU	11,233	4.31	4.00	3.68	4.02	2.78	2.35	1.98						
			4.46	4.13	3.71	3.25	2.81	2.41	2.05	6607.6	25.0		19.5	.41E-01	.49E+01 *
289.000	Cent/MODU	11,194	4.13	3.82	3.49	3.81	2.63	2.19	1.82						
			4.28	3.95	3.52	3.07	2.64	2.24	1.90	6380.3	25.0		21.2	.43E-01	.49E+01 *
306.000	Cent/MODU	11,265	4.26	3.94	3.57	3.96	2.59	2.14	1.74						
			4.46	4.07	3.58	3.08	2.61	2.19	1.83	5314.3	25.0		22.5	.57E-01	.56E+01 *
320.000	Cent/MODU	11,213	4.20	3.91	3.55	3.95	2.61	2.15	1.75						
			4.41	4.03	3.56	3.07	2.61	2.20	1.85	5563.5	25.0		22.1	.57E-01	.55E+01 *
336.000	Cent/MODU	11,225	4.13	3.83	3.52	3.81	2.59	2.15	1.73						
			4.33	3.96	3.51	3.03	2.58	2.18	1.84	5799.1	25.0		22.2	.49E-01	.53E+01 *
351.000	Cent/MODU	11,273	4.12	3.83	3.51	3.80	2.59	2.14	1.78						
			4.30	3.95	3.51	3.04	2.60	2.20	1.86	6075.2	25.0		22.0	.46E-01	.51E+01 *
368.000	Cent/MODU	11,170	4.35	4.01	3.62	4.02	2.59	2.13	1.74						
			4.56	4.14	3.62	3.10	2.62	2.19	1.83	4931.7	25.0		22.4	.59E-01	.57E+01 *
382.000	Cent/MODU	11,221	4.02	3.72	3.37	3.74	2.46	2.03	1.69						

Table 4. Continued.

			4.19	3.83	3.39	2.92	2.49	2.10	1.76	5875.3	25.0		23.3	.54E-01	.55E+01	*
397.000	Cent/MODU	11,198	4.35	4.05	3.72	3.97	2.69	2.16	1.66							
			4.64	4.19	3.65	3.11	2.61	2.18	1.81	4634.4	25.0		22.8	.62E-01	.66E+01	*
413.000	Cent/MODU	11,221	4.31	4.01	3.74	3.98	2.70	2.19	1.77							
			4.56	4.16	3.66	3.15	2.67	2.25	1.88	5225.1	25.0		21.8	.53E-01	.61E+01	*
427.000	Cent/MODU	11,178	4.31	4.00	3.67	3.99	2.69	2.21	1.75							
			4.54	4.14	3.65	3.14	2.66	2.24	1.88	5226.6	25.0		21.8	.55E-01	.58E+01	*
442.000	Cent/MODU	11,217	3.99	3.71	3.41	3.72	2.54	2.15	1.82							
			4.14	3.82	3.42	2.99	2.58	2.21	1.88	6513.6	98.7		20.8	.43E-01	.50E+01	&
457.000	Cent/MODU	11,146	4.42	4.10	3.70	4.13	2.74	2.23	1.76							
			4.65	4.23	3.72	3.19	2.70	2.26	1.89	4938.4	25.0		21.5	.62E-01	.60E+01	*
473.000	Cent/MODU	11,206	4.30	4.01	3.66	3.97	2.75	2.31	1.91							
			4.47	4.13	3.68	3.21	2.77	2.36	2.00	6177.5	25.0		20.1	.41E-01	.48E+01	*
488.000	Cent/MODU	11,237	4.04	3.75	3.40	3.68	2.41	1.92	1.49							
			4.31	3.87	3.35	2.83	2.36	1.96	1.61	4685.0	25.7		25.7	.66E-01	.66E+01	*
503.000	Cent/MODU	11,190	4.28	3.99	3.65	3.95	2.73	2.28	1.87							
			4.47	4.11	3.66	3.19	2.73	2.32	1.97	6002.2	25.0		20.5	.43E-01	.49E+01	*
520.000	Cent/MODU	11,170	4.28	3.98	3.63	3.93	2.72	2.30	1.93							
			4.43	4.10	3.66	3.20	2.76	2.35	2.00	6339.6	25.0		20.0	.39E-01	.47E+01	*
534.000	Cent/MODU	11,202	4.33	4.02	3.71	3.97	2.78	2.29	1.88							
			4.52	4.16	3.70	3.22	2.76	2.34	1.98	5882.3	25.0		20.4	.43E-01	.51E+01	*
548.000	Cent/MODU	11,051	4.42	4.11	3.64	4.15	2.76	2.29	1.83							
			4.61	4.22	3.73	3.22	2.74	2.32	1.95	5298.8	25.0		20.6	.57E-01	.57E+01	*
564.000	Cent/MODU	11,122	4.49	4.14	3.75	4.21	2.73	2.26	1.84							
			4.69	4.28	3.77	3.24	2.75	2.31	1.94	5026.5	25.0		20.9	.60E-01	.57E+01	*
578.000	Cent/MODU	11,055	4.48	4.08	3.67	4.20	2.61	2.13	1.67							
			4.71	4.24	3.68	3.12	2.61	2.16	1.79	4301.3	25.0		22.7	.76E-01	.63E+01	*
593.000	Cent/MODU	11,158	4.32	4.07	3.72	4.01	2.78	2.31	1.83							
			4.56	4.18	3.71	3.22	2.75	2.33	1.96	5610.1	25.0		20.6	.48E-01	.54E+01	*
Mean:			4.35	4.05	3.70	4.03	2.77	2.34	1.89	5893.9	64.8		20.5			
Std. Dev:			0.20	0.20	0.19	0.20	0.20	0.23	0.31	1228.0	122.5		2.9			
Var Coeff(%):			4.67	4.83	5.08	4.91	7.07	9.67	16.20	20.8	189.1		14.1			

3.2 CASE B: IH10 BEAUMONT, TX - CORNER/EDGE SLAB DATA ANALYSIS

This case study is a continuation of Case A, where in order to demonstrate the LTE/Void detection module, FWD deflections were collected at the corner and edge locations. The same section of IH10 (in Orange County, Beaumont, Texas) was used as the test section for Case B. Downstream deflection data was collected using the set up described earlier in this report.

LTE/Void detection output lists the LTE calculated by the Uzan and the CTR method and void detection information given by the CTR method and the NCHRP methods. Table 5 lists the RMODS LTE/Void detection output for IH10. RMODS users have the option of checking the output at each station. Figure 8 illustrates a sample deflection bowl analysis and the summary of the analysis at station 32. RMODS indicated possible presence of voids or poor support conditions within the first 10 slabs. In order to validate this prediction of voids beneath the first 10 slabs, Ground Penetrating Radar and several holes were drilled at potential void locations. The GPR survey did detect what appeared to be wet areas beneath the joints primarily in the first 10 joints. Dry holes were drilled at three locations, and the results were not as clear. No voids were found at the bottom of the slab; however, what was found was a thin layer (6 mm thick) of old grout which had not set up. This grout had the consistency of toothpaste. Upon rechecking the construction records, it was found that the section had been grouted 5 years prior to the time of testing. In some locations this grout had not set up, thus leaving a weak paste beneath the slab.

The conclusion from this study was that the term void detection algorithm is probably misleading. The algorithms appear capable of detecting poor joint support conditions, which may or may not be an air or water filled void.

3.3 CASE C: US52 LEXINGTON, NORTH CAROLINA

Case C is performed on FWD data collected on a test section of US52 (Lexington, North Carolina). The test pavement was a new jointed concrete pavement 230 mm thick concrete slab over a 100 mm crushed aggregate base over select fill. Moisture was thought to be getting trapped in sections of this pavement. The primary concern of this case study is to check the condition of the subgrade.

Table 5. Summary of LTE/Void Detection Calculations.

Page: 1 TTI RIGID MODULUS LOAD TRANSFER/VOID DETECTION ANALYSIS SYSTEM (SUMMARY REPORT) (Version 2.0)

District: 20 County: 181 Highway/Road: IH0010

			*** Measured Deflection, (mils)/Sensor Sp. (in) ***							**** LOAD TRANSFER % ****				** VOID DETECTION **		
	Load Plate	Load	W1	W2	W3	W4	W5	W6	W7		****** C T R ******			CTR	**** NCHRP ****		
Station	* Location *	(lbs)	0.00	12.00	24.00	-12.00	36.00	48.00	60.00	LTE	DOR	QD	MD	Void	Int	Slope	Void
3.000	D/S Corner	9,947	15.92	13.29	10.69	2.15	6.43	4.90	3.80	14.2	16.2	21.6	66.3	YES	0.9	0.7	NO
17.000	D/S Corner	9,701	15.61	12.93	10.27	2.55	6.07	4.63	3.42	17.3	19.7	21.6	65.9	YES	1.6	0.7	NO
32.000	D/S Corner	9,149	15.58	12.98	10.55	2.75	6.52	4.89	3.86	18.5	21.2	20.8	66.6	YES	3.5	0.8	YES
48.000	D/S Corner	9,002	16.57	13.86	11.12	3.13	6.62	5.10	3.98	19.8	22.6	22.4	65.7	YES	2.5	0.7	YES
63.000	D/S Corner	9,145	16.38	13.57	11.04	2.76	6.72	5.16	4.05	17.8	20.3	21.6	64.9	YES	1.5	0.6	NO
78.000	D/S Corner	8,986	14.30	12.07	9.74	2.79	5.91	4.60	3.59	20.5	23.1	19.5	69.6	YES	-0.9	0.6	NO
93.000	D/S Corner	8,966	16.13	13.44	10.76	2.39	6.54	4.98	3.93	15.7	17.8	21.6	65.9	YES	1.3	0.6	NO
110.000	D/S Corner	9,224	12.93	10.75	8.65	2.57	5.07	3.86	2.98	21.0	23.9	17.9	70.0	NO	3.2	0.9	YES
126.000	D/S Corner	9,109	12.07	9.98	8.08	2.48	4.91	3.85	2.99	21.9	24.8	16.2	70.8	NO	0.8	0.8	NO
142.000	D/S Corner	8,998	14.65	12.22	9.95	2.19	6.14	4.75	3.64	15.6	17.9	19.7	68.0	YES	0.2	0.6	NO
156.000	D/S Corner	9,335	12.50	10.59	8.67	2.50	5.41	4.17	3.30	21.2	23.6	16.9	72.3	NO	1.5	0.9	NO
172.000	D/S Corner	9,057	11.86	9.97	8.14	3.33	4.97	3.94	3.13	29.4	33.4	15.9	72.5	NO	2.4	1.0	YES
188.000	D/S Corner	9,022	11.66	9.85	7.93	3.87	5.02	3.88	3.00	34.5	39.3	15.9	73.2	NO	-1.4	0.7	NO
203.000	D/S Corner	8,958	9.47	8.05	6.71	6.66	4.29	3.40	2.84	72.7	82.7	12.2	76.7	NO	0.4	1.0	NO
218.000	D/S Corner	8,938	10.74	9.02	7.38	3.87	4.68	3.65	2.87	38.1	42.9	14.4	74.0	NO	0.6	0.9	NO
235.000	D/S Corner	8,835	10.93	9.00	7.19	3.09	4.35	3.32	2.61	30.1	34.3	14.9	72.2	NO	0.5	0.8	NO
249.000	D/S Corner	9,006	8.77	7.18	5.80	3.30	3.48	2.69	2.09	40.3	46.0	12.0	75.2	NO	1.1	1.2	NO
267.000	D/S Corner	8,847	7.50	6.08	4.93	4.76	2.95	2.27	1.79	66.6	78.3	10.1	76.7	NO	0.4	1.3	NO
281.000	D/S Corner	9,181	10.39	8.43	6.66	2.65	3.91	2.94	2.33	27.3	31.4	14.3	71.9	NO	1.1	1.0	NO
297.000	D/S Corner	8,740	9.41	7.63	6.04	2.59	3.56	2.72	2.13	29.5	33.9	12.9	73.5	NO	0.2	0.9	NO
Mean:			12.67	10.54	8.52	3.12	5.18	3.99	3.12	28.6	32.7	17.1	70.6		1.1	0.8	
Std. Dev:			2.83	2.40	1.93	1.05	1.17	0.89	0.68	16.0	18.5	3.8	3.8		1.2	0.2	
Var Coeff(%):			22.33	22.73	22.63	33.76	22.57	22.25	21.80	55.8	56.6	22.3	5.4		111.4	23.0	

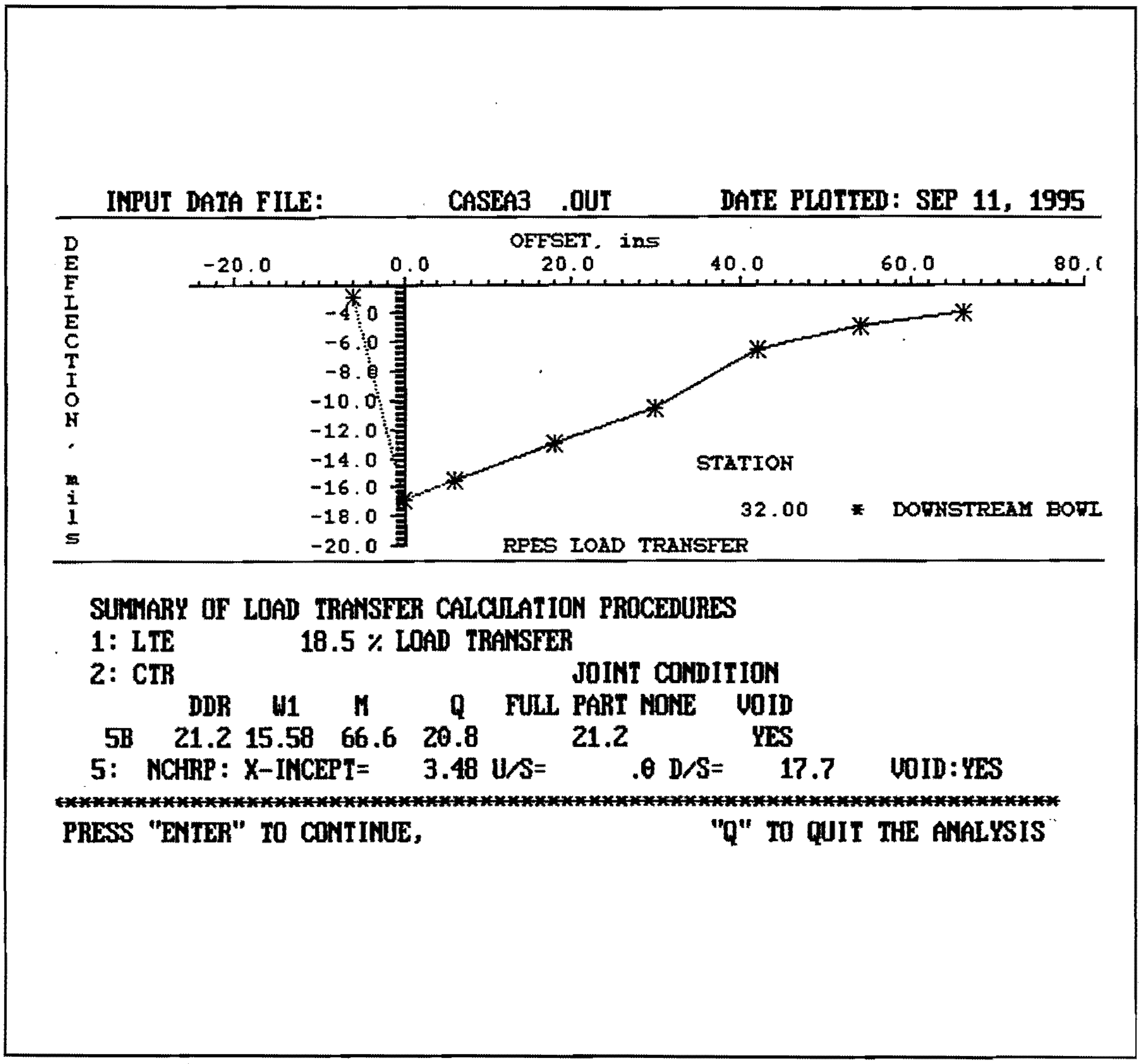

Figure 8. Deflection Bowl Analysis, Case B, IH10.

Falling Weight Deflectometer data was collected at the center slab location of the test sections. Data from one load level producing an approximate load of 10,000 lb was processed. In the data analysis using RMODS, a range of 15 ksi - 80 ksi was used for the value of elastic modulus of the base.

3.3.1 Results

Table 6 lists the results obtained from the Hertz analysis. Mean value of modulus of subgrade reaction k is found to be 167.7 pci, while E1 is found to be 8225 ksi. Table 7 lists the results obtained from layered elastic theory. Mean value obtained for E1 is low compared to that obtained from Hertz theory, which is 5680.2 ksi. The elastic modulus of the base is found to be relatively low at stations 5 to 41.

Table 6. Summary of Evaluation Parameters Obtained from Hertz Theory Case C - US52 Lexington, North Carolina.

Page: 1 TTI RIGID MODULUS BACKCALCULATION ANALYSIS SYSTEM (SUMMARY REPORT) (Version 2.0)

District: 10 County: 20 Highway/Road: US52 HERTZ THEORY, CENTER DEFLECTION

Station	*Load Plate* * Location *	Load (lbs)	** Measured/Computed Deflection, (mils): W1	W2	W3	W4	W5	W6	** W7	Modulus E, Radius of Relative Stiff-ness l, & Mod. of Subg. Reaction k E1	l	k	Err2	Err/ sens.
1.000	Cent/HERT	9,908	3.70	3.31	2.98	2.41	1.96	1.60	1.42					
			3.65	2.50	2.98	2.50	2.03	1.60	1.23	9071.8	41.3	197.4	.81E-01	.67E+01 &
5.000	Cent/HERT	9,864	3.81	3.43	3.04	2.49	1.93	1.57	1.27					
			3.75	2.54	3.04	2.54	2.04	1.60	1.21	8382.1	40.4	200.0	.74E-01	.60E+01 &
9.000	Cent/HERT	9,856	4.03	3.58	3.09	2.51	1.91	1.56	1.22					
			3.82	2.57	3.09	2.57	2.06	1.60	1.21	7970.9	39.8	201.3	.90E-01	.67E+01 &
13.000	Cent/HERT	9,876	3.91	3.43	2.98	2.35	1.78	1.44	1.14					
			3.76	2.44	2.98	2.44	1.92	1.46	1.08	7405.6	37.9	227.3	.96E-01	.73E+01 &
17.000	Cent/HERT	9,816	3.91	3.54	3.11	2.55	2.00	1.63	1.31					
			3.84	2.59	3.11	2.59	2.09	1.63	1.24	8100.0	40.2	195.6	.77E-01	.58E+01 &
21.000	Cent/HERT	9,796	4.04	3.75	3.25	2.73	2.12	1.75	1.39					
			4.04	2.72	3.27	2.72	2.18	1.70	1.29	7555.4	39.9	188.2	.83E-01	.59E+01 &
25.000	Cent/HERT	9,741	4.01	3.73	3.30	2.81	2.29	1.91	1.56					
			3.92	2.84	3.30	2.84	2.38	1.94	1.55	10307.9	45.9	146.4	.59E-01	.47E+01 &
29.000	Cent/HERT	9,594	5.31	4.91	4.44	3.74	2.94	2.38	1.87					
			5.31	3.74	4.40	3.74	3.08	2.47	1.94	6729.5	43.5	119.1	.62E-01	.53E+01 &
33.000	Cent/HERT	9,618	4.59	4.27	3.89	3.37	2.78	2.30	1.90					
			4.59	3.37	3.89	3.37	2.84	2.34	1.89	9185.3	47.2	117.4	.45E-01	.37E+01 &
37.000	Cent/HERT	9,598	5.43	5.06	4.52	3.89	3.11	2.58	2.00					
			5.45	3.84	4.52	3.84	3.17	2.55	2.00	6629.0	43.7	115.0	.58E-01	.41E+01 &
41.000	Cent/HERT	9,717	4.17	3.87	3.33	2.83	2.26	1.84	1.47					
			4.02	2.83	3.33	2.83	2.33	1.88	1.47	9041.9	43.6	158.3	.75E-01	.51E+01 &
45.000	Cent/HERT	9,586	4.35	3.91	3.55	3.02	2.41	2.00	1.63					
			4.29	3.02	3.56	3.02	2.49	2.00	1.57	8320.7	43.5	146.6	.55E-01	.45E+01 &
Mean:			4.27	3.90	3.46	2.89	2.29	1.88	1.51	8225.0	42.2	167.7		
Std. Dev:			0.57	0.57	0.54	0.52	0.44	0.37	0.28	1072.9	2.8	38.7		
Var Coeff(%):			13.24	14.62	15.75	17.90	19.10	19.53	18.68	13.0	6.5	23.1		

Table 7. Summary of Evaluation Parameters Obtained from Layered Elastic Theory Case C - US52 Lexington, North Carolina.

Page: 1 TTI RIGID MODULUS BACKCALCULATION ANALYSIS SYSTEM (SUMMARY REPORT) (Version 2.0)

District: 10 County: 20 Highway/Road: US52 LAYERED THEORY, CENTER DEFLECTION

Station	*Load Plate* * Location *	Load (lbs)	W1	W2	W3	W4	W5	W6	W7	E1	E2	E3	ESG	Err2	Err/ sens.
			**** Measured/Computed Deflection, (mils): ****							Modulus E, of the Pavement Layers					
1.000	Cent/MODU	9,907	3.70	3.31	2.98	2.41	1.96	1.60	1.42						
			3.69	3.34	2.88	2.42	2.01	1.65	1.36	6880.1	66.2		26.4	.48E-02	.22E+01 &
5.000	Cent/MODU	9,863	3.81	3.43	3.04	2.49	1.93	1.57	1.27						
			3.88	3.47	2.94	2.42	1.96	1.58	1.27	5821.3	15.0		29.0	.27E-02	.17E+01 *
9.000	Cent/MODU	9,855	4.03	3.58	3.09	2.51	1.91	1.56	1.22						
			4.09	3.62	3.01	2.44	1.95	1.55	1.23	4848.8	15.0		29.7	.23E-02	.17E+01 *
13.000	Cent/MODU	9,875	3.91	3.43	2.98	2.35	1.78	1.44	1.14						
			3.96	3.48	2.87	2.31	1.83	1.44	1.14	4724.5	15.0		32.1	.26E-02	.15E+01 *
17.000	Cent/MODU	9,815	3.91	3.54	3.11	2.55	2.00	1.63	1.31						
			3.98	3.57	3.02	2.49	2.03	1.63	1.32	5700.5	15.0		27.9	.18E-02	.14E+01 *
21.000	Cent/MODU	9,795	4.04	3.75	3.25	2.73	2.12	1.75	1.39						
			4.15	3.74	3.18	2.64	2.15	1.74	1.41	5648.0	15.0		25.9	.29E-02	.17E+01 *
25.000	Cent/MODU	9,740	4.01	3.73	3.30	2.81	2.29	1.91	1.56						
			4.08	3.73	3.25	2.76	2.30	1.91	1.58	7000.0	17.3		22.8	.96E-03	.96E+00 *
29.000	Cent/MODU	9,593	5.31	4.91	4.44	3.74	2.94	2.38	1.87						
			5.51	4.97	4.26	3.55	2.92	2.38	1.94	4328.0	15.0		18.2	.72E-02	.27E+01 *
33.000	Cent/MODU	9,617	4.59	4.27	3.89	3.37	2.78	2.30	1.90						
			4.68	4.32	3.81	3.27	2.76	2.32	1.93	6782.3	15.0		18.1	.22E-02	.16E+01 *
37.000	Cent/MODU	9,597	5.43	5.06	4.52	3.89	3.11	2.58	2.00						
			5.60	5.10	4.41	3.72	3.09	2.54	2.09	4665.3	15.0		16.9	.58E-02	.25E+01 *
41.000	Cent/MODU	9,716	4.17	3.87	3.33	2.83	2.26	1.84	1.47						
			4.26	3.85	3.30	2.75	2.26	1.84	1.50	5717.6	15.0		24.2	.17E-02	.12E+01 *
45.000	Cent/MODU	9,585	4.35	3.91	3.55	3.02	2.41	2.00	1.63						
			4.39	4.00	3.46	2.92	2.43	2.00	1.65	6044.8	19.7		21.3	.24E-02	.16E+01 &
Mean:			4.27	3.90	3.46	2.89	2.29	1.88	1.51	5680.2	19.9		24.4		
Std. Dev:			0.57	0.57	0.54	0.52	0.44	0.37	0.28	905.3	14.7		5.0		
Var Coeff(%):			13.24	14.62	15.75	17.90	19.10	19.53	18.68	15.9	73.9		20.5		

CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

From the implementation and case study of the RMODS, the following conclusions are made. These conclusions and recommendations are the authors, opinions and do not reflect the views of the Texas Transportation Institute. It is recommended that the user of the RMODS program interpret the results from this case study at his/her own discretion.

- The computer software RMODS developed under the rigid pavement evaluation system of the Texas Department of Transportation is successfully tested to evaluate a few in-service rigid pavements.
- The elastic modulus of concrete E1 (or E_c) calculated from Hertz model is consistently higher than those calculated by layered elastic theory, which are found to be closer to the realistic values.
- Elasticity moduli E1 deduced by the Hertz model are found to be directly proportional to the peak FWD deflections.
- Low values of elastic modulus of subgrade (E_{sg}) and modulus of subgrade reaction (k) are found at places where voids are confirmed.
- The elastic modulus of the base layer was not accurately evaluated by the elastic theory, which might be due to the non-convergence. This problem was more pronounced in the pavements with low base layer thicknesses.
- High deflection values at the joints revealed low load transfer efficiencies of the joints.
- The CTR method of void detection was more successful that the NCHRP method in detecting voids under the concrete slabs.

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