An Efficient and Accurate Genetic Algorithm for Backcalculation of Flexible Pavement Layer Moduli

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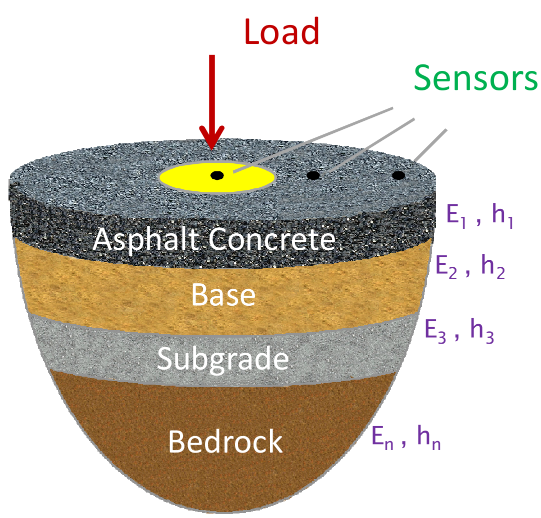

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16. Abstract

The importance of a backcalculation method in the analysis of elastic modulus in pavement engineering has been known for decades. Despite many backcalculation programs employing different backcalculation procedures and algorithms, accurate inverse of the pavement layer moduli is still very challenging. In this work, a detailed study on the backcalculation of pavement layer elastic modulus and thickness using genetic algorithm is presented. Falling weight deflectometer (FWD) data is generated by applying a load to the pavement and measuring pavement deflection at various fixed distances from the load center. The measurement errors in FWD data are simulated by perturbing the theoretical deflections. Based on these data, backcalculation technique is performed using an improved genetic algorithm (GA). Besides root mean square (RMS), another objective function called area value with correction factor (AVCF) is proposed for accurate backcalculation of pavement modulus and thickness. The proposed backcalculation method utilizes the efficient and accurate program MultiSmart3D for the forward calculation and it can backcalculate the modulus and thickness simultaneously for any number of pavement layers. A simple, user-friendly, and comprehensive program called *BackGenetic3D* is developed using this new backcalculation method which can be utilized for any layered structures in science and engineering.

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ABSTRACT

The importance of a backcalculation method in the analysis of elastic modulus in pavement engineering has been known for decades. Despite many backcalculation programs employing different backcalculation procedures and algorithms, accurate inverse of the pavement layer moduli is still very challenging. In this work, a detailed study on the backcalculation of pavement layer elastic modulus and thickness using genetic algorithm is presented. Falling weight deflectometer (FWD) data is generated by applying a load to the pavement and measuring pavement deflection at various fixed distances from the load center. The measurement errors in FWD data are simulated by perturbing the theoretical deflections. Based on these data, backcalculation technique is performed using an improved genetic algorithm (GA). Besides root mean square (RMS), another objective function called area value with correction factor (AVCF) is proposed for accurate backcalculation of pavement modulus and thickness. The proposed backcalculation method utilizes the efficient and accurate program MultiSmart3D for the forward calculation and it can backcalculate the modulus and thickness simultaneously for any number of pavement layers. A simple, user-friendly, and comprehensive program called *BackGenetic3D* is developed using this new backcalculation method which can be utilized for any layered structures in science and engineering.

CHAPTER 1 INTRODUCTION

1.0 INRODUCTION

Backcalculation of pavement moduli has been an intensively researched subject for more than four decades. Despite the existence of many backcalculation programs employing different backcalculation procedures and algorithms, the accuracy of the moduli values is still controversial. All of the classical backcalculation procedures require seed moduli to initiate the backcalculation process. Different seed moduli often lead to different backcalculated moduli which in turn lead to different pavement designs and evaluations, adding more challenges to engineers (Alkasawneh *et al* 2007).

The main problems any classical backcalculation procedure faces are convergence, accuracy, and the number of layers in the backcalculation program. The selection of the seed moduli controls the convergence of the backcalculation procedure to pavement moduli that minimizes the mean square error (of the objective function) between the measured deflection and the backcalculated deflection using the backcalculated moduli. It is known that more than one solution could satisfy the objective function criterion in the backcalculation of the pavement moduli due to the multimodal nature of the backcalculation search space where many local optima exist. In turn, arrival at local optima will lead to “inaccurate” pavement moduli that can be as much as twice the “accurate” value. On the other hand, the maximum number of layers that can be used in any existing backcalculation program can handle at most 5 layers with recommendations to use 3 layers to reduce the error associated with the backcalculation process. In some cases, increasing the number of layers in the backcalculation process is desirable to obtain more representative variation of the moduli with depth.

Genetic algorithms (GAs) can be used to backcalculate the pavement moduli by searching the entire search space of the objective function using guided random search techniques. The GAs are based on the Darwinian theory and are formulated on the mechanics of genetics and natural selection (Holland, 1975; Goldberg, 1989). The objectives of this work are to study the GA-based backcalculation method in pavement materials, to optimize the objective function in backcalculation procedure, to develop a new user-friendly backcalculation program (*BackGenetic3D*), to generalize the backcalculation procedure to include arbitrary number of pavement layers, loading conditions, loading configuration, and number of sensors, and last but not least to validate the performance and accuracy of the new method using several real pavement cases.

In this work, the Introduction section is presented in Chapter 1 which provides an overview of the recent research in backcalculation and the understanding of the theory of elasticity in pavement. Chapter 2 represents a visual basic application (VBA) in Microsoft Excel utilized to collect data from long term pavement performance (LTPP) program. Chapter 3 discusses the deflection data screening and the related VBA code. Chapter 4 describes the general overview of backcalculation as well as the development of the proposed genetic algorithm. Objective functions and their applications are presented in Chapter 5. Chapter 6 introduces the new backcalculation software (*BackGenetic3D*). Several numerical examples are presented in Chapter 7 to show the capability of the *BackGenetic3D* program. Chapter 8 presents the concluding remarks and future recommendations of the research and engineering work.

1.1 OVERVIEW OF BACKCALCULATION RESEARCH

Solutions to the problem of surface loading over an elastic half space or layered structures are important to various technology and science fields including pavement engineering. Numerous analytical and/or numerical methods were proposed in the past to solve the circular loading problem in inhomogeneous elastic isotropic (Pan 1989; Oner *et al* 1990; Yue *et al* 2005) and elastic non-isotropic (Hooper 1975, Rowe and Booker 1981, Kumar 1988, Doherty and Deeks 2003) structures. More recently, Chu *et al* (2011) studied the surface loading problem corresponding to a layered, transversely isotropic magnetoelectroelastic half space while Wang *et al* (2012) studied the circular surface loading on an anisotropic magnetoelectroelastic half space. Experimentally, nondestructive tests (NDTs) are commonly performed on existing pavements to measure the surface deflections, which in turn are used to backcalculate the elastic moduli of the pavement layers. Different methods have been proposed by researchers to estimate the elastic modulus based on laboratory tests and empirical equations (Bonnaure *et al* 1977), wave propagation methods (Szendrei and Freeme 1970), and the falling weight deflectometer (FWD).

Since its introduction in 1970's (Ullidtz 1987), the falling weight deflectometer (FWD) has been widely used in nondestructive tests throughout the world (FHWA-LTPP Technical Support Services Contractor 2000). The nondestructive test involves applying impact loads to a loading plate while measuring the vertical displacement on the surface of the pavement at different locations. The measured deflections from the FWD test along the pavement surface are then utilized to backcalculate the modulus of elasticity in each layer. While numerous approaches were proposed for backcalculation of layer modulus and thickness (Khazanovich *et al* 2001; Irwin 2002; Von Quintus and Simpson 2002; Alkasawneh 2007; Alkasawneh *et al* 2007a; Pan *et al* 2008), there are still many ambiguous factors that could substantially affect the accuracy of the backcalculation. Stubstad *et al* (2000) reported that in the long-term pavement performance (LTPP) database, some FWD deflection sensors were mislocated and these sensors could yield major inaccuracies in backcalculated moduli. Calibration of FWD (Irwin and Richter 2005; Orr *et al* 2007) and temperature variation (Xu *et al* 2002; Alkasawneh *et al* 2007b) are also important issues in backcalculation of pavement properties.

While error measurement in FWD data are very common in practical pavement engineering (e.g., Irwin and Richter, 2005), there is still no efficient computational approach to handle those errors. Irwin *et al* (1989) analyzed the sources of deflection errors and illustrated, through a series of examples, how random errors in pavement deflection and thickness could affect backcalculated moduli. Using the backcalculation program MODULUS (Uzan *et al* 1989) for different pavement structures, Jooste *et al* (1998) found that even allowable and small variation in layer thickness could significantly influence the backcalculated moduli. So far however, the effect of measurement errors on the backcalculation has not been thoroughly investigated. Acknowledging the inevitable existence of measurement errors, we propose a new objective function within the perspective of mathematical optimization to weaken and even eliminate the effect of measurement errors on backcalculation.

Systematic and random errors are the two types of measurement errors recognized by pavement engineers. Due to the influence of temperature and/or improper operations (Xu *et al* 2002; Irwin and Richter 2005; Orr *et al* 2007; Alkasawneh *et al* 2007b), systematic errors always exist whilst random errors cannot be eliminated. There are several calibration methods to deal with measurement errors. Strategic highway research program (SHRP) calibration procedure can reduce the systematic error to a large extent by periodic calibration of the FWD. However, the usage of this method is limited since it needs a lot of measurement data at a test point as well as a skilled operator.

Genetic algorithm (GA) as a robust and randomized search algorithm (Goldberg 1989) can be employed to optimize the search domain for backcalculation. The use of GAs in pavement engineering is relatively new and thus no thorough investigation has been carried out to address all aspects and challenges associated with the backcalculation procedure. There are numerous backcalculation programs listed in Alkasawneh *et al* (2007b). Most programs can only perform backcalculation for up to 20 layers of pavement due to the limitations associated with the mathematical formulation of their analytical solutions. This limitation restricts the modeling of pavement structures where the temperature variation is observed along the depth. *BackGenetic3D* is a program developed by The University of Akron group which uses GA and the efficient and accurate forward program *MultiSmart3D* to backcalculate the thickness as well as the layer moduli of any pavement structure with no restrictions regarding the number of layers, thickness, location of the response points, number of loading circles, the shape of the loading area, and the type of applied loads. This program is the first in the world that can backcalculate the pavement moduli with arbitrary number of layers, loading conditions, and loading types.

Several methods have been developed to backcalculate the mechanical properties of flexible pavement. These methods vary in analysis type, material model, and optimization algorithm. In a comparative study, Goktepe *et al* (2006) explained these methods and compared them in terms of modeling precision, computational expense, and calculation details. While Goktepe *et al* (2006) considered only the static case, Seo *et al* (2009) studied the dynamic effects of the deflection on the backcalculation procedure. It is found that the DYN-BAL (Dynamic BALMAT), a pseudo-static backcalculation procedure, gives very reliable results compared to several computer codes in use. Gopalakrishnan and Papadopoulos (2011) employed a novel machine learning concept called conformal prediction (CP) in pavement backcalculation confidence estimation which uses past experience to determine precise levels of confidence in new predictions. The backcalculation of pavement layer moduli and Poisson's ratio using data mining (DM) method was proposed by Saltan *et al* (2011).

1.2 ELASTICITY IN PAVEMENT

Poisson's ratio is the ratio of the contraction or transverse strain (perpendicular to the applied load), to the extension or axial strain (in the direction of the applied load). Poisson's ratio is an important material property that is considered to be one of the characteristics of the material. The minimum value of Poisson's ratio is close to -1 which happens for some structural materials called Auxetics. Human bone, paper and some polymeric materials could also have a negative Poisson's ratio. The maximum value of Poisson's ratio is close to 0.5 which happens for several polymers like elastomers. Poisson's ratio for cork is close to zero which means almost no lateral contraction under applied tensile or compressive load. Poisson's ratio is usually measured by tensile test on materials samples using several sensors at the edges of the sample.

For materials that are important in geotechnical engineering, construction, and pavement engineering, Poisson's ratio is not easy to calculate exactly. Therefore, in most engineering works a range of Poisson's ratios can be considered. Table 1.1 shows a typical range of Poisson's ratio for different materials in pavement layers.

According to the standard of ASTM D5858 (ASTM 2003), the Poisson's ratio of the subgrade should be selected carefully. Small variations in this value may cause significant differences in the mechanical response in the upper pavement layers. Also it is important to note that the Poisson's ratio of unbound granular base and cohesive soil layers strongly depends on the stress/strain level and degree of soil saturation.

Another important characteristic of materials is the elastic modulus that is defined as the tendency of a material to deform elastically. Elastic modulus or Young's modulus is very important especially in mechanical behavior of materials. For most polymeric materials, elastic modulus has a small value while for most metals it has a medium value. The maximum natural value of elastic modulus is about 1220 GPa (170000 ksi) for diamond. Also for carbon nanotubes and graphene, elastic modulus is almost 1000 GPa (145000 ksi) which is responsible for growing applications of these materials.

Table 1.1 Poisson's ratios for pavement layers

Asphalt concrete	0.30 - 0.40
Portland cement concrete	0.10 - 0.20
Unbound granular base	0.20 - 0.40
Cohesive soil	0.25 - 0.45
Cement-stabilized soil	0.10 - 0.30
Lime-stabilized soil	0.10 - 0.30

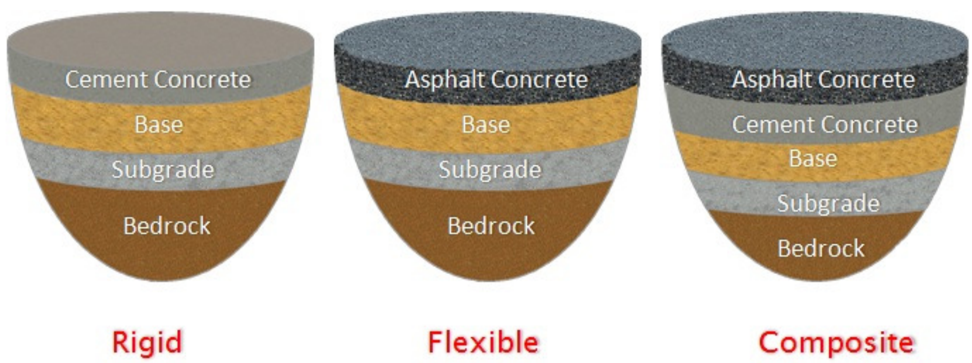


Figure 1.1 Schematic illustration of three types of pavement.

Table 1.2 Seed values of elastic modulus for pavement layers

Asphalt concrete	500 ksi (3500 MPa)
Portland cement concrete	5000 ksi (35000 MPa)
Cement-treated bases	600 ksi (4100 MPa)
Unbound granular bases	30 ksi (200 MPa)
Unbound granular subbases	15 ksi (100 MPa)
Cohesive soil	7 ksi (50 MPa)
Cement-stabilized soil	50 ksi (350 MPa)
Lime-stabilized soil	20 ksi (140 MPa)

It is important to remember that a measure of a material's modulus of elasticity is not a measure of its strength. Strength is the stress needed to break a material, whereas elasticity is a measure of how well a material returns to its original shape and size.

Figure 1.1 schematically shows the different types of pavement. In pavement engineering many programs require a range of acceptable moduli values for each layer to improve the speed of operation and to limit the moduli to their practical values. In *BackGenetic3D* program the range of elastic modulus will be available as an input data. Table 1.2 shows the typical seed value of the elastic modulus for pavement layers.

In the *BackGenetic3D* program the range of elastic moduli has been defined that can be entered for each layer of the pavement. Fig. 1.2 illustrates the *Initial Information* dialogue for *BackGenetic3D* program. Upon selecting the type of pavement in the *Initial Information* window, a default value will be assigned to the total number of layers. The default values for the range of elastic modulus could be those recommended by AASHTO and GA algorithm as in Table 1.3. Also, the AASHTO typical Poisson's ratios as well as the elastic moduli are presented in Table 1.4. It is noted that all these values can be modified by the user using the user-friendly interface of the *BackGenetic3D* program.

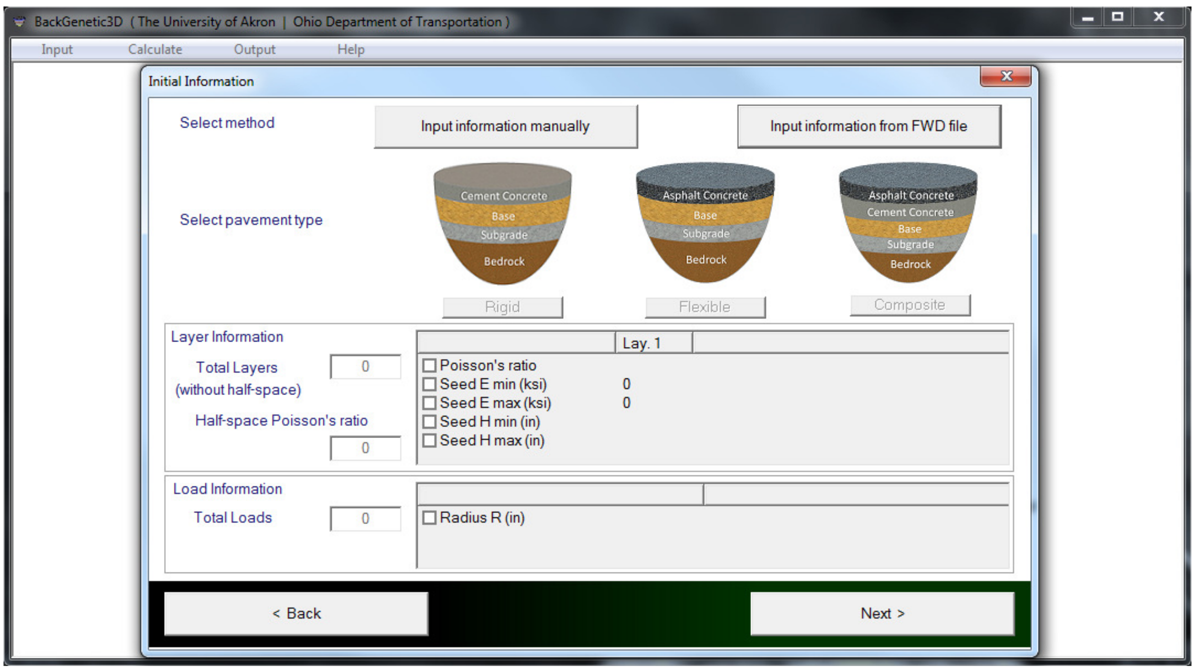


Figure 1.2 *Initial Information* dialog in *BackGenetic3D* program.

Table 1.3 Recommended AASHTO and GA range for elastic moduli

Material	Recommended AASHTO Range (ksi) MPa	Recommended GA Range (ksi) MPa
Hot-Mix Asphalt	(217.6 - 507.6) 1500 - 3500	(145.0 - 580.2) 1000 - 4000
Portland Cement Concrete	(2900.8 - 7977.1) 20000 - 55000	(2610.7 - 8702.3) 18000 - 60000
Asphalt-Treated Base	(72.5 - 435.1) 500 - 3000	(43.5 - 507.6) 300 - 3500
Cement-Treated Base	(507.6 - 1015.3) 3500 - 7000	(362.6 - 1160.3) 2500 - 8000
Lean Concrete	(1015.3 - 2900.8) 7000 - 20000	(870.2 - 3625.9) 6000 - 25000
Granular Base	(14.5 - 50.8) 100 - 350	(11.6 - 65.3) 80 - 450
Granular Subgrade Soil	(7.3 - 21.8) 50 - 150	(4.4 - 36.3) 30 - 250
Fine-Grained Subgrade Soil	(2.9 - 7.3) 20 - 50	(1.5 - 14.5) 10 - 100

Table 1.4 AASHTO's typical Poisson's ratios and elastic moduli

Material	Range of Modulus (ksi) MPa		Typical Modulus (ksi) MPa		Range of Poisson's Ratio ν	Typical Poisson's Ratio ν
Hot-Mix Asphalt	(217.6 - 507.6)	1500 - 3500	(435.1)	3000	0.15 - 0.45	0.35
Portland Cement Concrete	(2900.8 - 7977.1)	20000 - 55000	(4351.1)	30000	0.10 - 0.20	0.15
Asphalt-Treated Base	(72.5 - 435.1)	500 - 3000	(145.0)	1000	0.15 - 0.45	0.35
Cement-Treated Base	(507.6 - 1015.3)	3500 - 7000	(725.2)	5000	0.15 - 0.30	0.20
Granular Base	(14.5 - 50.8)	100 - 350	(29.0)	200	0.30 - 0.40	0.35
Granular Subgrade Soil	(7.3 - 21.8)	50 - 150	(14.5)	100	0.30 - 0.40	0.35
Fine-Grained Subgrade Soil	(2.9 - 7.3)	20 - 50	(4.4)	30	0.30 - 0.40	0.35

1.3 MODULI CALCULATION: IMPACT TO PAVEMENT DESIGN

Today, engineers simultaneously use the knowledge of theoretical calculations and take advantage of the experimental results. The theoretical calculations are mainly based on the elastic theories which help engineers to acquire stresses, strains, and deflections in the pavement. The pavement is the portion of the highway that consists of durable materials. Deficient pavement condition can result in increased user costs, travel delays, braking and fuel consumption, vehicle maintenance repairs, and probability of increased crashes. The condition of the highway is commonly judged by the smoothness or roughness of the pavement. The pavement life is substantially affected by the number of applied heavy load repetitions. This phenomenon is called fatigue: the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. A properly designed pavement structure will also take into account the applied load.

The design equations for pavement presented in 1986 AASHTO design guide were obtained empirically from the results of AASHO road test. To develop a mechanistic pavement and design procedure, a research project entitled "Calibrated Mechanistic Structural Analysis Procedures for Pavements" was awarded to the University of Illinois (Thompson 1992). The research includes both flexible and rigid pavements, and a two-volume report was prepared for the National Cooperative Highway Research Program (Lytton *et al* 1990). Flexible pavement is created from a combination of materials that are mixed together to be paved and compacted later on the road surface while rigid pavement is a technical term for any road surface made of concrete (Fig. 1.3). Each layer in flexible pavement receives the load from the above layer and passes it to the layer below. In contrast, the largest advantage of using a rigid pavement is its durability and ability to hold its shape.

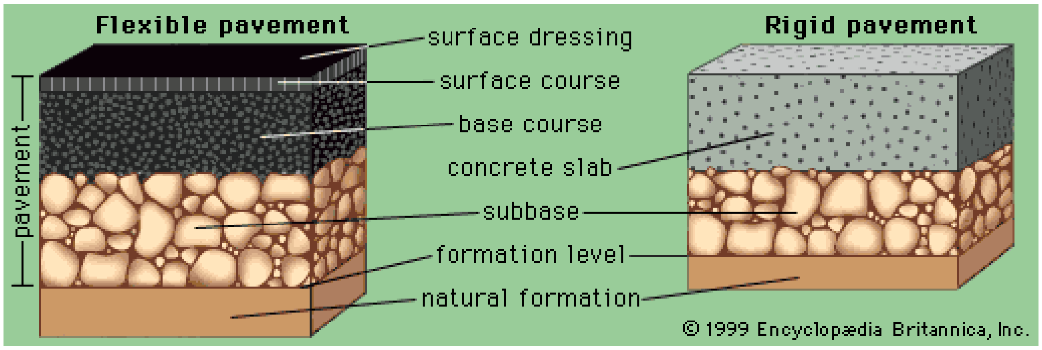


Figure 1.3 Flexible and rigid pavement structures.

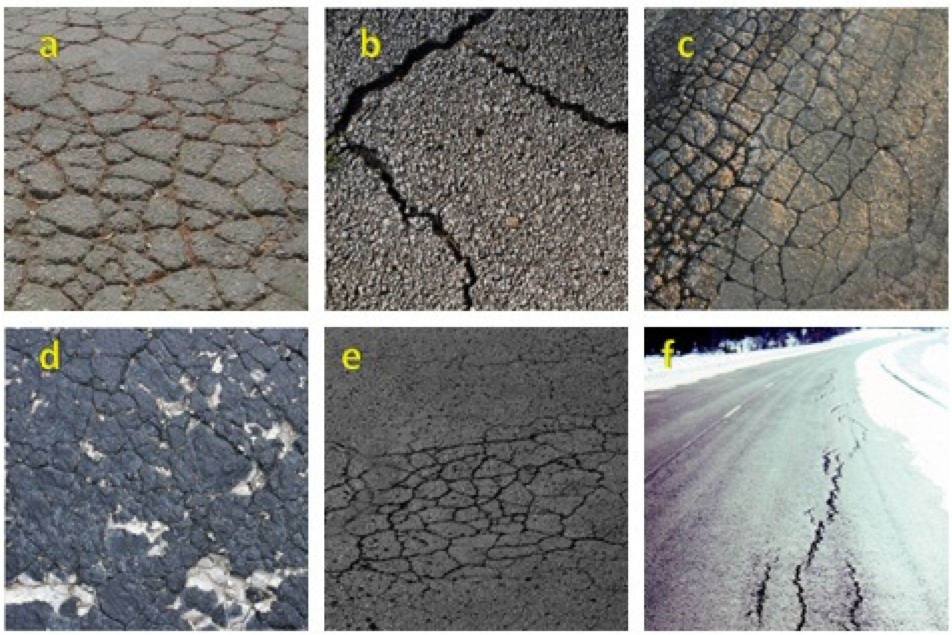


Figure 1.4 Different imperfections in the pavement: (a) spider-webbing (b) cracking (c) corroding (d) bubbling (e,f) fatigue cracking.

Paved roads are typically either flexible or rigid depending on the traffic loading, subgrade support, and the availability and cost of material. In thin pavements, cracking initiates at the bottom of the hot mix asphalt (HMA) layer where the tensile stress is the highest, and then propagates to the surface as one or more longitudinal cracks. This is commonly referred to as "bottom-up" or "classical" fatigue cracking. In thick pavements, the cracks most likely initiate from the top in areas of high localized tensile stresses resulting from tire-pavement interaction and asphalt binder aging (top-down cracking). After repeated loading, the longitudinal cracks connect, forming many-sided sharp-angled pieces that develop into a pattern resembling the back of an alligator or crocodile. Fig. 1.4 shows the typical imperfections due to fatigue and thermal changes on the surface of the asphalt pavement materials. There are several design models for fatigue and rutting prediction as presented in the next sections.

1.3.1 DESIGN MODEL FOR FATIGUE

The damage of flexible pavements can be assessed by predicting the number of load repetitions needed to initiate cracks (fatigue cracking). There are two most frequently used models in flexible pavements. The Shell model is based on the work of Bonnaure *et al* (1980), which has two expressions depending upon the layer thickness. The first one is

$$N_f = A_f K F'' \left(\frac{1}{\varepsilon_t} \right)^5 E_s^{-1.4} \qquad \text{Eq. (1.1)}$$

where N_f is the number of load repetitions to fatigue cracking, F'' is a constant that depends on the layer thickness and the material stiffness, ε_t is the tensile strain at the bottom of the AC layer, E_s is the stiffness of the material, and A_f and K are material constants.

This equation illustrates the Shell model in constant strain condition which is applicable to thin layers. The other Shell constant stress model is applicable to thick layers. This fatigue model is called the Asphalt Institute model which is given by the following equation,

$$N_f = 0.00432 C \left(\frac{1}{\varepsilon_t} \right)^{3.291} \left(\frac{1}{E_s} \right)^{0.854} \qquad \text{Eq. (1.2)}$$

where C is a material constant. Actually, this model can be used for pavement layer of any thickness.

It can be seen from the above equations the critical tensile strain and the stiffness of the layer are the main factors affecting the number of load repetitions needed to initiate fatigue failure.

1.3.2 DESIGN MODEL FOR RUTTING

According to the Asphalt Institute and Shell design methods, the allowable number of load repetitions N_r to rutting failure is related to the compressive strain ε_v on the top of the subgrade.

$$N_r = c_1 \left(\frac{1}{\varepsilon_v} \right)^{c_2} \qquad \text{Eq. (1.3)}$$

where N_r is the number of allowable load repetitions until rutting failure, ε_v is the maximum compressive strain at the top of the subgrade layer, and c_1 and c_2 are the subgrade strain criteria. The values of c_1 and c_2 are based on the evaluation of various agencies. In MnROAD rutting model these values are suggested to be 5.5×10^{15} and 3.929, respectively. Equations (1.1) to (1.3) are the most applicable models for predicting the fatigue and rutting in pavements.

The effect of backcalculated elastic moduli on fatigue can be evaluated by the ratio between the estimated number of repeated loads (N_f) using the backcalculated elastic moduli and that using the exact set of elastic moduli. It is important to note that even though the error in deflection measurement is small, the fatigue and rutting life based on the backcalculated and exact moduli could still be very different.

CHAPTER 2 LTPP DATABASE EXPLORATION

2.0 INTRODUCTION

It is important to determine the in-situ pavement material properties in pavement engineering. The procedure of determining the pavement properties using experimental deflections produced by given loads is referred to as backcalculation. The widely used nondestructive test (NDT) to record the dynamic loading and the corresponding surface deflection is the falling weight deflectometer (FWD). In FWD test, surface deflection under dynamic loading is recorded and material moduli are then determined based on a trial-and-error procedure by matching the computed deflections with the measured ones. Our project is focused on developing an efficient and accurate algorithm for the backcalculation of pavement layer moduli and thicknesses.

As for the first task of the whole project, this report documents the method for collecting the laboratory data of FWD loads and deflections which are the basis for the backcalculation. The laboratory data are collected from the long-term pavement performance (LTPP) program. It is the largest and most comprehensive pavement study database and we will mainly introduce how to export the data file from the website and how to extract the useful records from the downloaded data file by using a simple visual basic application (VBA) in Microsoft Excel. We have written a special VBA code which can be very efficiently used to deal with any Excel format deflection data file from the LTPP website. The deflection curves along the test locations can be graphed easily which have been verified by the curves on the LTPP website.

2.1 PAVEMENT LAYER PROFILE

Before executing the backcalculation procedure to calculate the moduli of the pavement materials, we first need to have the pavement structures of each highway section. In the LTPP database, there are totally 76 tested highway sections in Ohio. The backcalculation will be based on these experimental records of material profiles and FWD deflections. Note that for all the available highway sections in Ohio, the pavement materials are given layer by layer and in each layer the material property is homogeneous rather than the mixture of different materials with functionally graded material (FGM) properties. For each highway section, we record the layer numbers, layer materials and thickness of each layer. As part of the Task 1 for the whole project, the laboratory data and in-situ data of pavement structures in all highway sections in Ohio have been collected from LTPP database and are listed in Appendix B (Table B.1). In the table, the left column records the code of each section and the right one lists the material names, layer orders (the top row denotes the surface layer) and layer thickness.

2.2 THE LTPP TOOL SOFTWARE

For most highway sections, the FWD deflection data files include thousands of measured records that are tested at different time and/or under different conditions. These records are not easily handled directly in the Microsoft Excel environment. There is a need for pavement researchers to collect these deflection records in a faster and more flexible way. Based on the data screening program, an Excel-based VBA program with a user friendly interface is developed to process the FWD deflection data file and plot the deflection curves according to users' selection of the test condition. The program can directly search the condition items in the data file and automatically assign them to the User Dialog rather than let the users provide it themselves. Deflections measured on different dates can be easily plotted on one figure and their comparison implies the pavement stiffness changing over time. It is noted that the data for flexible pavements requires to be corrected for temperature variations. The program can serve as an auxiliary tool to the LTPP online product and it is applicable to the deflection data file of all the highway sections.

Appendix C expresses how to load the program in Microsoft Excel 2003 and 2007. The LTPP tool program was developed as Microsoft Excel Add-In file, of which the filename extension is "*.xla*". When the Add-In file "LTPP TOOL.*xla*" is loaded, a new menu named "LTPP TOOL" appears on the menu bar of EXCEL window as shown in Fig. 2.1. By clicking the new menu item the program will be launched. Four UserForms have been designed in the program as described in the following: Start Page; Filter Conditions; Plot Average Deflections and Plot Separate Deflections.

2.2.1 START PAGE

When the program is launched, a simple Start Page named "LTPP TOOL" (Fig. 2.2) appears, including one command button named "START" and other brief texts. Clicking the button "START", a second UserForm called "Filter Conditions" will appear as shown in Fig. 2.3.

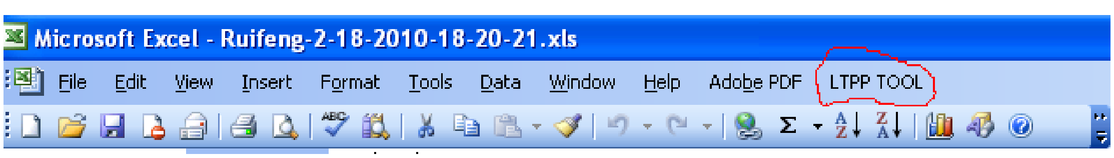


Figure 2.1 Microsoft Excel menu bar with an Add-In menu "LTPP TOOL".

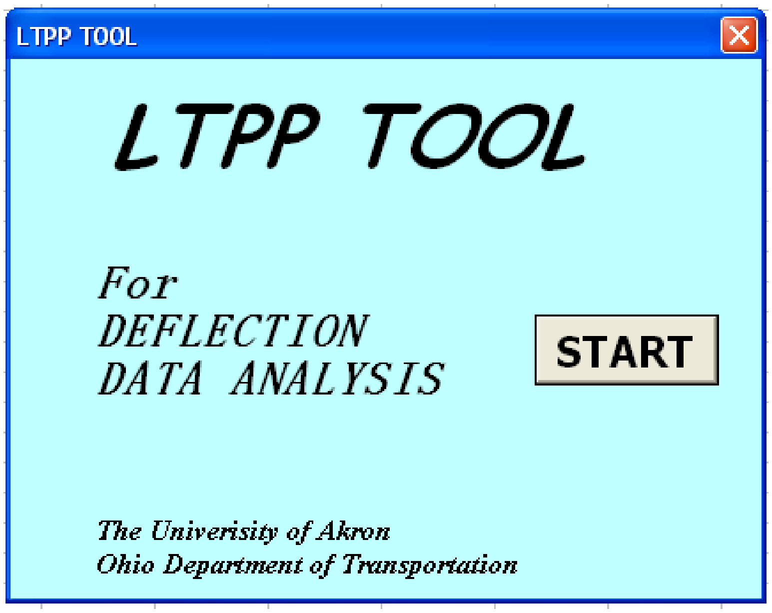


Figure 2.2 Start page in LTPP TOOL.

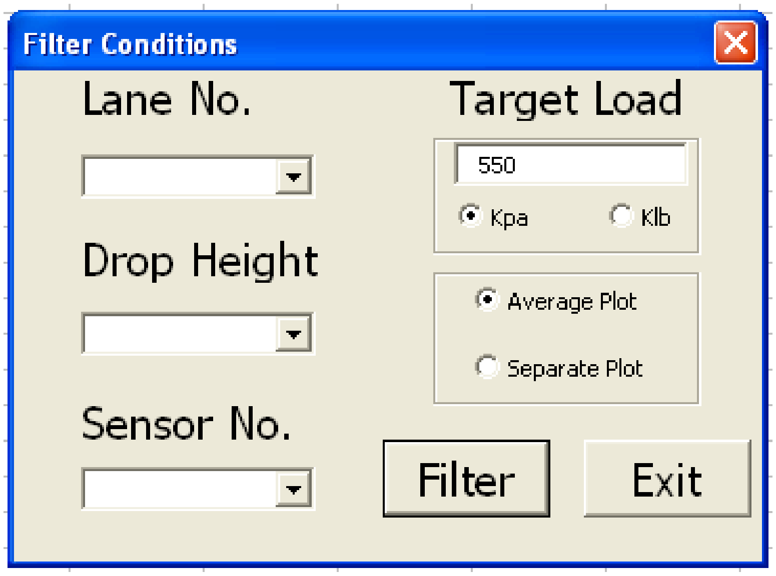


Figure 2.3 UserForm “Filter Conditions” in LTPP TOOL.

2.2.2 FILTER CONDITION

Combobox “Lane No.”

At the same time the UserForm starts, the program is searching through the column “LANE_NO” of the data file while assigning all appeared items to the Combobox “Lane No.”.

Combobox "Drop Height"

Picking any item from the Combobox "Lane No.", the program will search through the column "DROP_HEIGHT" and only those rows of which the cell values at column "LANE_NO" equal to the selected item are searched. All appeared drop heights will be assigned to the Combobox "Drop Height".

Combobox "Sensor Number"

For any single test, there are nine measured deflections at nine different sensors and the measured peak deflections at these sensors are named from "PEAK_DEFL_1" to "PEAK_DEFL_9". Thus, at the same time when UserForm is initialized, the Combobox "Sensor No." is assigned with nine sensor names.

Frame "Target Load"

The column "Drop Load" records the peak of the measured load for one test and the deflection is produced by the falling weight. Even the drop weight and drop height are fixed for different tests, the measured peak drop load could still be different, and furthermore, it is not easy to fix the drop load at a fixed value. However, only the measured deflections under the same load condition could have the comparative significance. Therefore, for all test records, the drop load is preferably normalized with a fixed load. In this UserFrame, Kpa means the peak pressure on the drop plate (with 300 mm diameter) which is applied to the pavement and Klb means the total load on the drop plate which is applied to the pavement. This means that a normalized pressure of 550 Kpa is approximately equivalent to a normalized load of 9 Klb. In order to be consistent with the LTPP online product, the default drop load is set at 550 Kpa or 9 Klb. If other drop load is used, the program will automatically convert between the units of Kpa and Klb.

Plotting Option Buttons

Even though the three test conditions discussed above are all determined, for some highway sections, the test records sometimes are still not unique since some tests are carried out several times under exactly the same condition. Therefore, two options are provided in the program: one is "Plot Average" which means to plot only the average value of several deflection records corresponding to the same test condition and the other is "Plot Separately" which means to separately plot each deflection record for the same test condition.

Command Button "Filter"

By clicking the command button "Filter", the program will search all records coincident with the test condition defined above and create two new worksheets. One is called "sheet1" which is used to save all the matched records. Deflections under the same filter condition but with different drop numbers are all listed. The other is called "result" in which the deflection records will be averaged. At the same time, the next UserForm “Plot Average Deflections” or “Plot Separate Deflections” will be activated.

Command Button “Exit”

As the “Exit” button in any other software, by clicking on it, the program will exit. But all newly created worksheets are kept as they are.

2.2.3 PLOT AVERAGE DEFLECTIONS

If the option button “Plot Average” in the UserForm “Filter Conditions” is selected, the “Filter” button will activate and initialize the UserForm “Plot Average Deflections” (Fig. 2.4).

Plotting Option Buttons

Option buttons “Straight” and “Smooth” respectively mean that the deflection data will be connected with straight and smooth lines. Checking the option at any time, even if the deflection curves have been plotted, they will be automatically changed to the corresponding line style.

Combobox “Test Date”

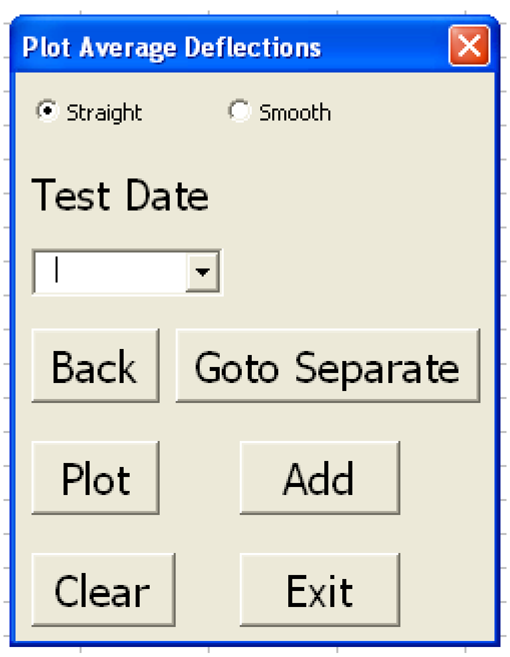


Figure 2.4 UserForm “Plot Average Deflections” in LTPP TOOL.

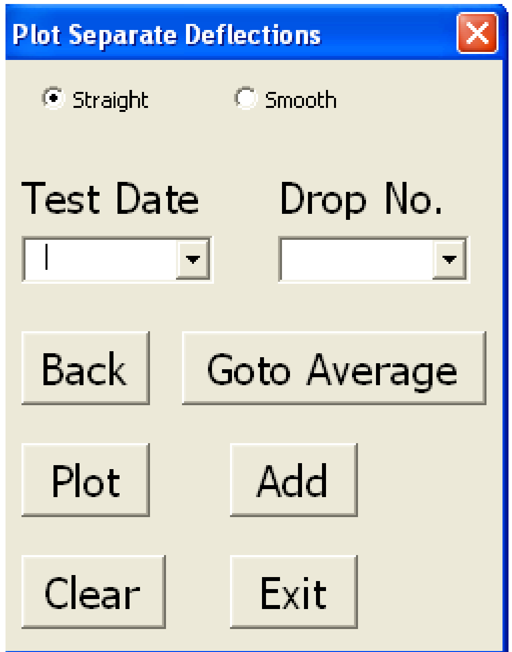


Figure 2.5 UserForm "Plot Separate Deflections" in LTPP TOOL.

At the same time when the UserForm is initialized, the program searches through the sheet "result", finds out all possible test dates and assigns them to the Combobox "Test Date". These items in the test date box are the last condition before plotting the deflection curves.

Command Button "Back"

By clicking the "Back" button, the UserForm "Filter Conditions" will be activated at the same way when the button "Start" in the first UserForm is clicked. In other words, the filter condition UserForm will be initialized again and all test conditions which has been determined before will be lost.

Command Button "Goto Separate"

This button is a convenient way to transit from UserForms "Plot Average Deflections" to "Plot Separate Deflections" (Fig. 2.5). This is equivalent to clicking the option button "Separate Plot" in the UserForm "Filter Conditions"

Command Button "Plot" and "Add"

Once any item in the Combobox "Test Date" is selected, all test conditions will be determined and thus the deflection curve can be plotted by clicking the command button "Plot". The program creates a new chart named "Figure" and searches through the column "TEST_DATE" in the sheet "result" to find the rows where the test date is coincident with the selected one in the Combobox "Test Date". Then the cells at these rows and columns "POINT_LOC" and "PEAK_DEFL_n" are used to plot the deflection curves in chart "Figure". The "n" in "PEAK_DEFL_n" is dependent on the selection at the UserForm "Filter Conditions". Note that the "Plot" command can only be used to plot a single curve in one figure. If there are more than one deflection curve that needs to be plotted in one figure, the command button "Add" should be used. By clicking "Add" button, the program will keep the existing curves and add a new one according to the selection of the test date. Moreover, the button "Plot" will delete all previously saved curves in the figure and only plot the one corresponding to the current date selection. As an example of the program operation result, Figure 2.6 shows three deflection curves for three different test dates.

Command Button "Clear"

By clicking the "Clear" command, the chart "Figure" is deleted and of course, all deflection curves are deleted as well.

Command Button "Exit"

If one clicks the "Exit" button, the program will stop running while all charts and worksheets are still retained.

2.2.4 PLOT SEPARATE DEFLECTIONS

If the option button "Plot Separate" in the UserForm "Filter Conditions" is selected, the "Filter" button will activate and initialize the UserForm "Plot Separate Deflections" (Fig. 2.5). Except for the Combobox "Test No." and the command button "Goto Average", all other boxes and buttons on this UserForm are exactly the same as those on the UserForm "Plot Average". As discussed in the previous section where the button "Goto Separate" on the UserForm "Plot Average" can activate the current UserForm, the "Goto Average" button on the current UserForm can activate the UserForm "Plot Average". For some highway sections, there are several deflection records under the same test condition and each one is assigned with a different drop number. In some cases, it is preferable to plot all these deflections one by one rather than plot their average values. Therefore, when the test date is selected from the Combobox "Test Date", the program adds the corresponding drop numbers to the Combobox "Drop No." After determining both test date and drop number, the corresponding deflection curve can be plotted on the chart "Figure" by clicking "Plot" or "Add" button. Figure 2.7 shows the deflection curves for highway section 39_0103 with test condition: LANE_NO = F1, DROP_HEIGHT = 2 and Sensor = PEAK_DEFL_1. There are more than one drop number for test dates "11/4/1996" and "4/11/2001", and the deflections of the two drop numbers are plotted respectively. The averaged deflections of test date “4/11/2001” are also plotted.

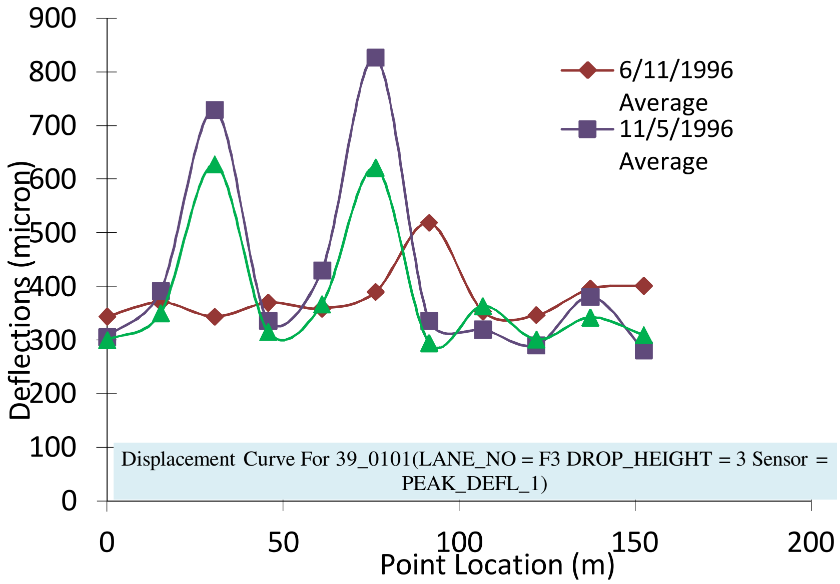


Figure 2.6 Deflection curves tested on different dates.

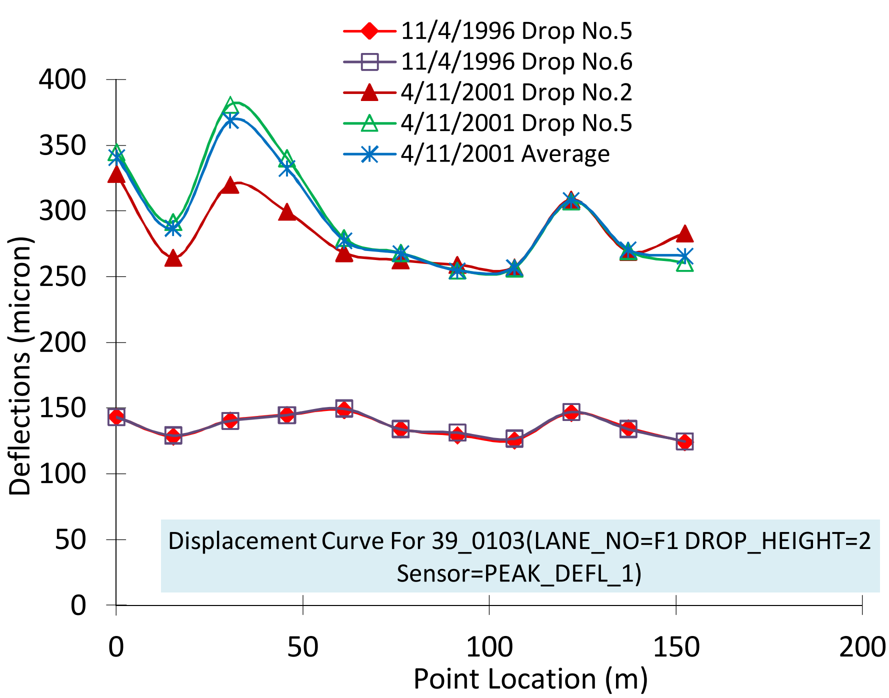


Figure 2.7 Deflection curves with different drop numbers.

CHAPTER 3 DEFLECTION DATA SCREENING

3.0 INTRODUCTION

As discussed in the previous chapter, The LTPP TOOL provides a faster and flexible way to collect the deflection records for any local area in the United States from the online database. In this chapter, the recorded deflections will be screened, and examples and verification are presented for this purpose.

3.1 DATA SCREENING CONDITION

For each highway section, the detailed FWD test data were stored in the Table MON_DEFL_DROP_DATA which can be exported as a Microsoft Excel or Access file as stated previously in section 2.1. In the 24 items included in the Appendix A.2, there are 7 items which provide the general information on the test and have no influence on the test results: STATE_CODE, SHRP_ID, DEFL_UNIT_ID, HISTROY_STORED, NON_DECREASING_DEFL, CONSTRUCTION_NO and RECORD_STATUS. There are 10 items which record the test results: PEAK_DEFL_1~PEAK_DEFL_9 and DTE. The DTE stands for computed deflection transfer efficiency across joints and cracks and the computation has not been implemented in the table. The left 7 items are used to indicate the experimental conditions, including TEST_DATE, POINT_LOC, DROP_NO, TEST_TIME, LANE_NO, DROP_HEIGHT and DROP_LOAD. These condition items may have different values and are composed of different groups of experimental conditions. For example, in the Excel file of the section 39-0101-1, there are totally 1106 test results with different experimental conditions such as different test time, different drop load, different drop height and different drop number, etc. However, these records are mixed together and it is difficult to observe the deflection patterns if no data sorting is executed. Therefore, by using the Visual Basic Application (VBA) attached in Microsoft Excel software, we have written a code to sort the deflection data and graph the corresponding result.

Generally, we are interested in the deflection curves from the test point to the start of the section, tested for the same lane number and under constant drop load and drop height. Because the test method is based on the falling weight, the drop load is difficult to be fixed even when the drop weight is the same, and thus the recorded drop loads can be very different. When we sort the deflection results, it is better to scale the deflection data by normalizing the varied loads to a fixed one. It can be seen that in the exported test result file, for each drop height, there are a series of tests conducted along a continuous increasing distance. Thus, the two arrays LANE_NO and DROP_HEIGHT are the conditions we selected and applied to the data sorting. Once we have determined these two values, the VBA program can filter all matched data based on which the deflection curve similar to the one in Figure 3.1 can be plotted. In the following section, we take "39-0101-1" as an example to show how to filter the deflection data and introduce the VBA code specially designed to manage the MON_DEFL_DROP_DATA file.

The exported table MON_DEFL_DROP_DATA of section 39-0101-1 in Excel format is composed of 24 columns (each column named as one of the above 24 items) and 1106 rows. Each row denotes a specific test. For example, for the first row, the values of 24 items are listed and explained as following:

- TEST_DATE = 8/29/1995 : The date when the test was conducted.
- STATE_CODE = 39 : Denote the State of Ohio.
- SHRP_ID = 0101 : Highway section number.
- DEFL_UNIT_ID = 8002-036 : The model of the FWD test device.
- POINT_LOC = 0 : The distance from the test point to the start of the section.
- DROP_NO = 1 : There may be more than one test under the same test condition. This is the first.
- TEST_TIME = 1029 : The specific time when the test was conducted is 10:29.
- LANE_NO = S3 : The lane number where the test point is located on S3.
- PEAK_DEFL_4 = 39 : The tested deflection at sensor 4 is 39 microns.
- DROP_HEIGHT = 1 : The falling weight was dropped from the first height set.
- DROP_LOAD = 181 : The tested drop load is 181 kPa.
- DTE : The deflection transverse efficiency has not been computed.
- HISTORY_STORED = N : There is no previously stored data for this drop.
- NON_DECREASING_DEFL = Null : Flag to identify deflection basin test records with non-decreasing deflections.
- PEAK_DEFL_1 = 382 : The tested deflection at sensor 1 is 382 microns.
- CONSTRUCTION_NO = 1 : This section has never been changed in pavement structure since it was accepted into LTPP.
- PEAK_DEFL_3 = 60 : The tested deflection at sensor 3 is 60 microns.
- PEAK_DEFL_5 = 28 : The tested deflection at sensor 5 is 28 microns.
- PEAK_DEFL_6 = 19 : The tested deflection at sensor 6 is 19 microns.
- PEAK_DEFL_7 = 9 : The tested deflection at sensor 7 is 9 microns.
- PEAK_DEFL_8 = : The tested deflection at sensor 8 is close to zero.
- PEAK_DEFL_9 = : The tested deflection at sensor 9 is close to zero.
- RECORD_STATUS = E : The data quality in IMS Quality Control is level E.
- PEAK_DEFL_2 = 120 : The tested deflection at sensor 2 is 120 microns.

	A	B	C	D	E	F	G
1	TEST_DATE	LANE_NO	DROP_HE	POINT_LO	PEAK_DE	PEAK_DEFL_7	
2	11/5/1996	F3	4	0	290.7655	37.56206	
3	11/5/1996	F3	4	15.2	384.6258	35.45707	
4	11/5/1996	F3	4	30.5	688.0278	48.90496	
5	11/5/1996	F3	4	45.7	323.8563	30.5939	
6	11/5/1996	F3	4	61	414.7788	29.11201	
7	11/5/1996	F3	4	76.2	779.433	41.08365	
8	11/5/1996	F3	4	91.4	328.9909	39.26601	
9	11/5/1996	F3	4	106.7	315.8399	45.85707	
10	11/5/1996	F3	4	121.9	293.5366	49.84852	
11	11/5/1996	F3	4	137.2	372.8545	50.49661	
12	11/5/1996	F3	4	152.4	287.0046	45.12027	
13	12/28/1996	F3	4	0	287.5118	36.78358	
14	12/28/1996	F3	4	15.2	362.1542	36.4641	
15	12/28/1996	F3	4	30.5	622.8689	48.94658	
16	12/28/1996	F3	4	45.7	313.2425	29.29059	
17	12/28/1996	F3	4	61	370.9834	27.40465	
18	12/28/1996	F3	4	76.2	604.1501	34.47065	
19	12/28/1996	F3	4	91.4	303.3326	38.19251	
20	12/28/1996	F3	4	106.7	365.0312	43.58594	
21	12/28/1996	F3	4	121.9	304.4696	47.17573	
22	12/28/1996	F3	4	137.2	347.2614	47.80849	
23	12/28/1996	F3	4	152.4	316.7888	43.02915	

Figure 3.1 The obtained results screened from MON_DEFL_DROP_DATA of Section 39-0101-1 with test condition LANE_NO = ”F3” and DROP_HEIGHT = ”4”.

3.2 VBA CODE INTRODUCTION

The VBA code for screening the tested deflections from the original exported data file is listed in Appendix D. Loading the VBA code into Microsoft Excel is also presented in Appendix E. Here, we briefly explain the code in the following paragraph:

- Line 1 is the common format for beginning a VBA code.
- Line 2 is declaring an integer array that will be used in the following codes.
- Loop from lines 3 to 9 is used to clear any empty or useless sheets if there is.
- Loop from lines 10 to 28 is used to search and locate the column number of the concerned test condition items.
- Lines from 29 to 48 are used to create a new sheet (named as “sheet1”) to record the filtered deflection data based on the manually specified test conditions as in line 33. The deflection results are not directly copied from the original file. Because the recorded DROP_LOAD for each test could be very different but we want to make it comparable, we have normalized all deflections by DROP_LOAD = 550 kPa (79.8 psi). Note that for one pair of test conditions,

i.e., POINT_LOC, LANE_NO and DROP_HEIGHT, there may be more than one conducted tests and more than one corresponding deflections. We therefore simply listed all these data in this sheet.

- Lines from 46 to 71 are used to create another sheet (named as "result") to deal with the data which are under the same load condition as stated in the paragraph above. All test data under the same condition are reduced to one row with the test conditions simply listed and the deflection cell is the averaged one.

If we set the test conditions as LANE_NO = "F3" and DROP_HEIGHT = "4", as shown in line 33 of the code, then the result file is shown in Fig. 3.1 and the deflection curves are shown in Figs. 3.2 and 3.3, which present, respectively, the test results on 11/5/1996 and 12/28/1996.

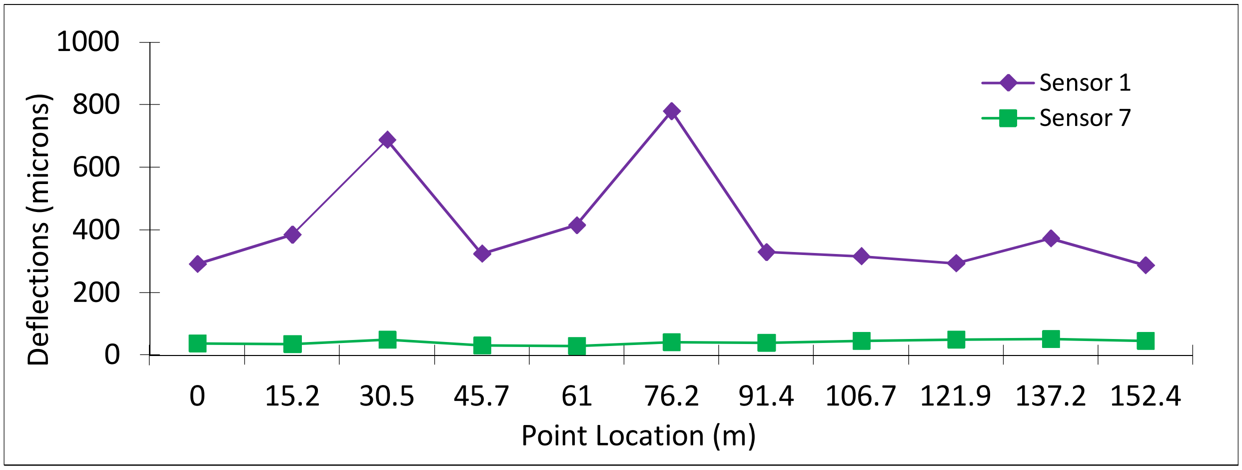


Figure 3.2 Deflection curve tested on 11/05/1996 with test conditions LANE_NO = "F3" and DROP_HEIGHT = "4".

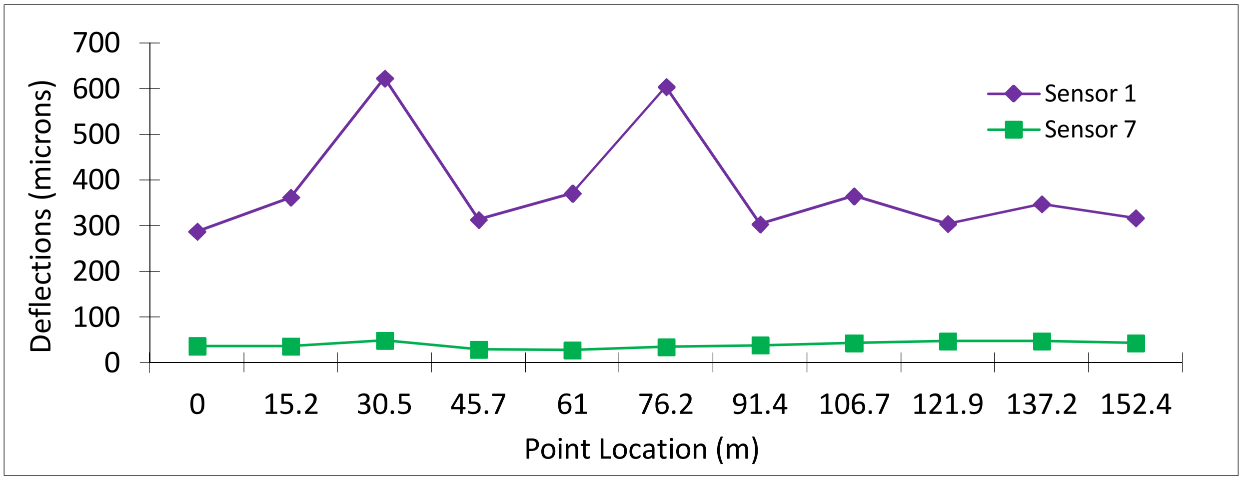


Figure 3.3 Deflection curve tested on 12/28/1996 with test conditions LANE_NO = "F3" and DROP_HEIGHT = "4".

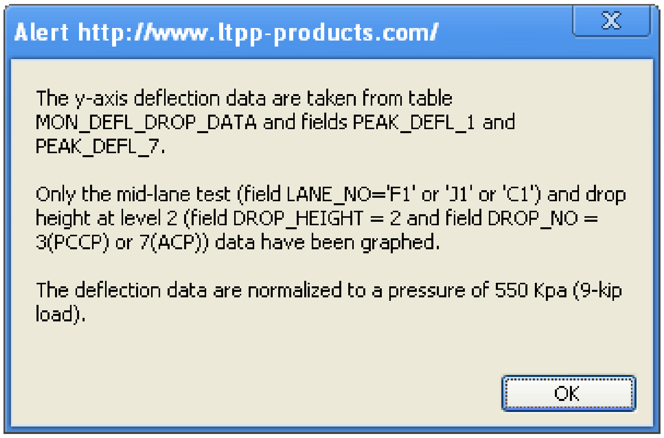


Figure 3.4 Pop-up window explaining the data source of deflection curves on LTPP website.

	A	B	C	D	E	F	G
1	TEST_DATE	LANE_NO	DROP_HE	POINT_LO	PEAK_DE	PEAK_DEFL_7	
2	6/11/1996	F1	2	0	307.8498	36.6041	
3	6/11/1996	F1	2	15.2	353.9696	27.87162	
4	6/11/1996	F1	2	30.5	332.8448	31.2931	
5	6/11/1996	F1	2	45.7	367.6166	36.09672	
6	6/11/1996	F1	2	61	347.0238	32.7381	
7	6/11/1996	F1	2	76.2	353.7037	27.77778	
8	6/11/1996	F1	2	91.4	461.2281	50.17544	
9	6/11/1996	F1	2	106.7	336.2694	47.49568	
10	6/11/1996	F1	2	121.9	340.566	44.33962	
11	6/11/1996	F1	2	137.2	411.0526	55	
12	6/11/1996	F1	2	152.4	411.2875	48.50088	
13	11/5/1996	F1	2	0	244.1046	41.34999	
14	11/5/1996	F1	2	15.2	321.0892	36.77681	
15	11/5/1996	F1	2	30.5	528.2868	47.24494	
16	11/5/1996	F1	2	45.7	257.0908	31.10542	
17	11/5/1996	F1	2	61	234.5324	25.55949	
18	11/5/1996	F1	2	76.2	586.6194	32.76482	
19	11/5/1996	F1	2	91.4	255.0694	39.38708	
20	11/5/1996	F1	2	106.7	292.7958	45.55662	
21	11/5/1996	F1	2	121.9	272.3807	50.23766	
22	11/5/1996	F1	2	137.2	292.1433	49.52392	
23	11/5/1996	F1	2	152.4	292.4267	45.35569	
24	12/28/1996	F1	2	0	245.7837	39.1072	
25	12/28/1996	F1	2	15.2	343.665	35.66342	
26	12/28/1996	F1	2	30.5	489.0991	43.26657	
27	12/28/1996	F1	2	45.7	309.702	26.95996	
28	12/28/1996	F1	2	61	268.4805	23.05271	
29	12/28/1996	F1	2	76.2	456.6416	32.14527	
30	12/28/1996	F1	2	91.4	280.3968	36.36886	
31	12/28/1996	F1	2	106.7	304.2757	41.85618	
32	12/28/1996	F1	2	121.9	291.1906	47.03433	
33	12/28/1996	F1	2	137.2	319.3719	46.03055	
34	12/28/1996	F1	2	152.4	303.5058	39.74196	

Figure 3.5 The obtained results screened from MON_DEFL_DROP_DATA of Section 39-0101-1 with test condition LANE_NO = ”F1” and DROP_HEIGHT = ”2”.

3.3 EXAMPLES AND VERIFICATION

To verify the correctness of our code, we set the test condition the same as that in the FWD deflection curves of Fig. 2.4. In that figure, if we click the ‘Data Source’ button below the deflection curve we can see the pop-up window shown in Fig. 3.4. It can be seen that the data condition is LANE_NO = ”F1” and DROP_HEIGHT = ”2”. After setting this condition in the VBA code, the result file is shown in Fig. 3.5. We plot the data of date 11/05/1996 and the deflection curve is shown in Fig. 3.6, which is exactly the same as in Fig. 2.4.

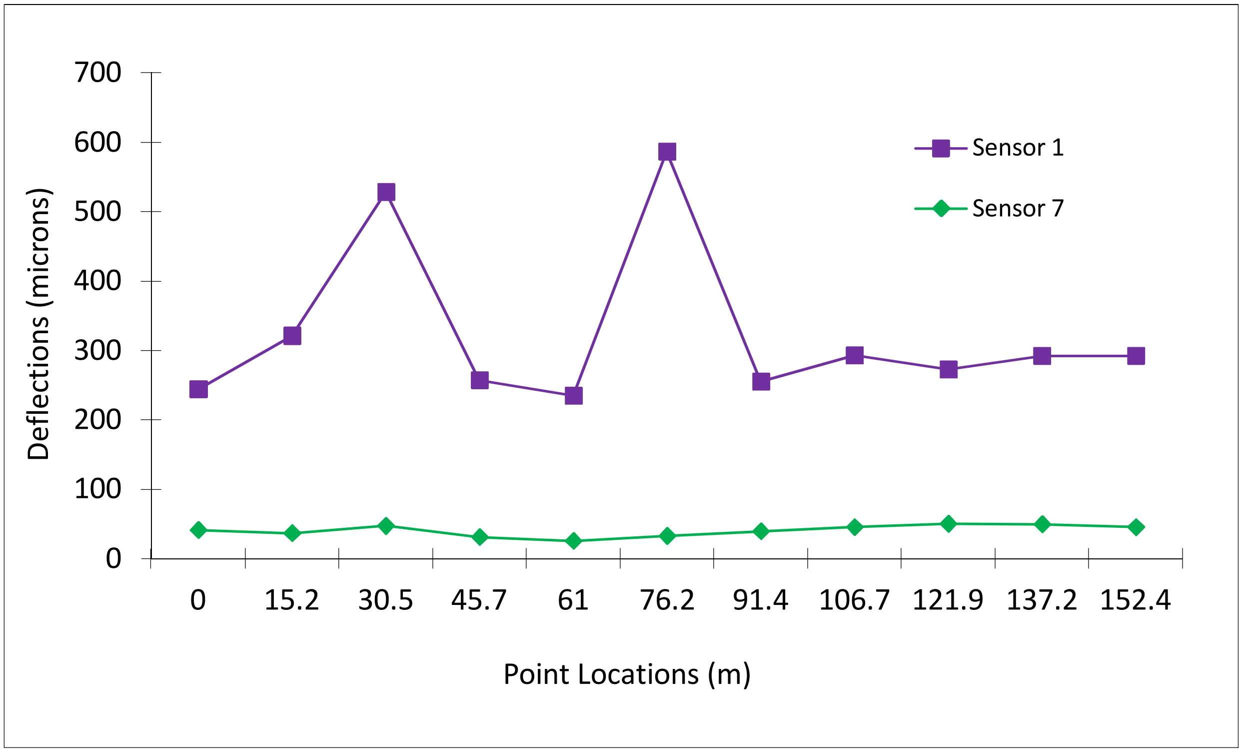


Figure 3.6 Deflection curve tested on 11/05/1996 for comparison to the LTPP data graph.

CHAPTER 4 THE BACKCALCULATION ALGORITHM

4.0 INTRODUCTION

This chapter presents the algorithm used for backcalculation of elastic modulus and thickness. The parameters of the input information as well as the forward and backward calculations are prescribed in the following sections. The genetic algorithm that has been improved is an important part of the backcalculation procedure and will be discussed in detail.

4.1 CODE SUMMARY

The backcalculation code for calculating layer modulus and layer thickness was developed in C++ platform, which mainly includes the following parts: input information, forward calculation using *MultiSmart3D*, genetic algorithm (GA) and result report. Note the GA discussed later in this chapter has been improved as compared with the traditional one and therefore, it is called improved genetic algorithm (IGA). The flow chart of the backcalculation code is illustrated in Fig. 4.1. The input information is included in the "Forward Initialize" section, the forward calculation is included in "Calculate Fitness" section, the result report is included in "Output Result" section, and all other sections are dealt by IGA. It is noted that only one set of layer information is calculated in each run of the code.

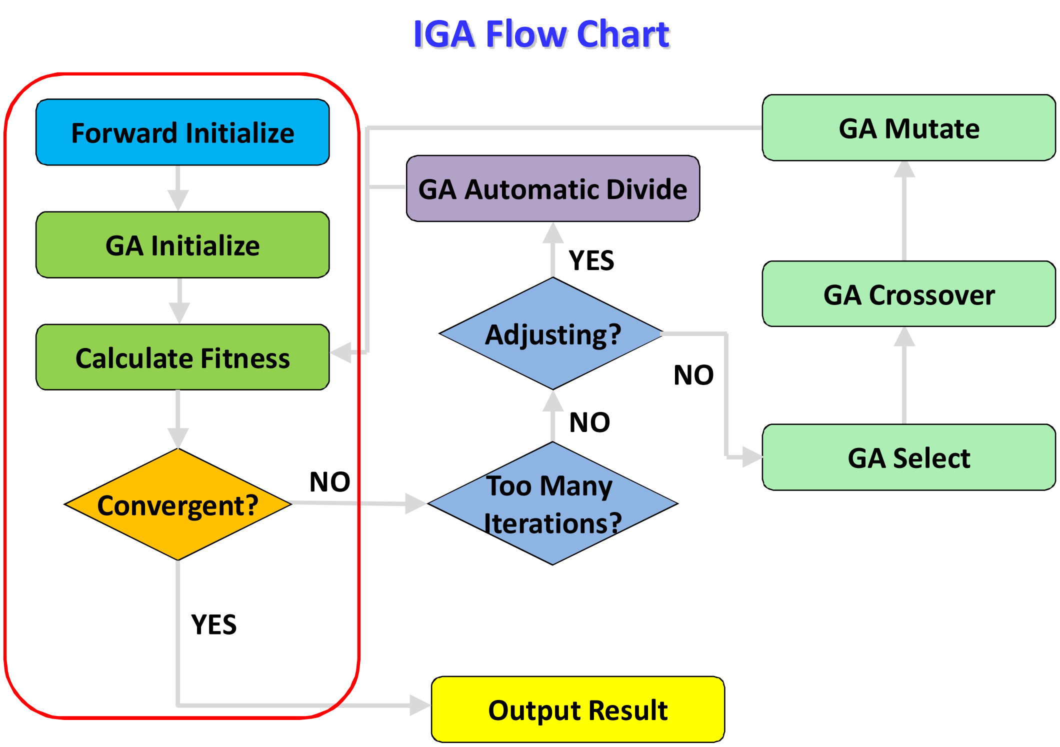


Figure 4.1 Backcalculation flowchart.

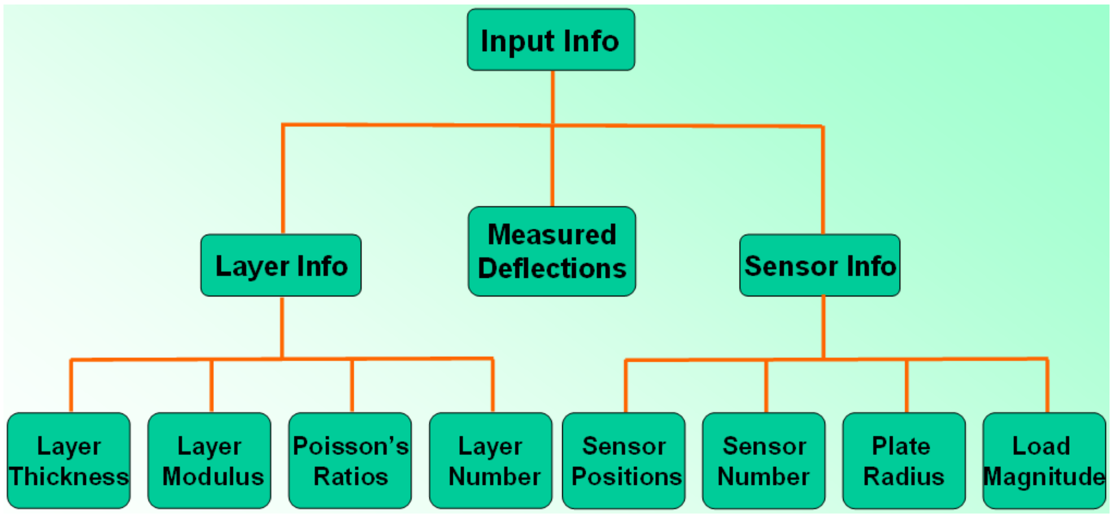


Figure 4.2 Structure of input information.

4.2 INPUT INFORMATION

The input information generally includes the layer information and sensor information. A user-defined data structure called "STRU_LAY_INFO" is constructed in the program which contains all layer information: layer modulus, layer thickness, layer Poisson's ratio and the total layer number (Fig. 4.2). In the current version of the program, the code backcalculates the layer modulus and layer thickness. The values for elastic modulus and thickness could be set arbitrarily in the input stage, and in the output stage these values are replaced by the calculated ones. Other layer properties, i.e., Poisson's ratios and total number of layers, need also to be defined at the beginning of the code, i.e., at the input stage. Another user-defined structure called "STRU_SENS_INFO" is constructed to handle the sensor information which generally includes sensor positions, number of sensors, load magnitude and the radius of the loading plate (Fig. 4.2). In FWD tests, there are usually 9 sensors laid out along a straight line and away from the center of the loading plate. These sensors are numbered according to their distance to the drop center. Sensor 1 is located at the center and sensor 9 is the farthest from the center. Usually only the first 7 sensors have been recorded with the deflection values. Thus, there should be 7 measured deflections in a single FWD test and their values become smaller as the sensor number increases. The deflection magnitudes are key inputs that may affect the accuracy of the backcalculated results significantly. Moreover, the program needs to deal with a lot of test data in a single run. Therefore, the deflection can be read from specially produced data in a file, so they can be separately treated in the program for convenience.

4.3 FORWARD CALCULATION

In the backcalculation procedure, the forward calculation is still very important because the GA always evaluates each individual deflection based on its fitness value which is related to the difference between the measured deflections and the forward-calculated ones (See objective functions discussed in Chapter 5). Therefore, in the backcalculation code, the forward subroutine is also called in the stage of "Calculate Fitness" (Fig. 4.1).

The forward subroutine is based on the layered elastic theory where the method of vector functions combined with the propagator matrix method is introduced to solve the deformation of layered and isotropic elastic materials under general surface loads. In so doing, one needs only to solve two systems of linear algebraic equations (2×2 and 4×4) in the transformed domain no matter how many layers there are in the layered structure. The adaptive Gauss quadrature is implemented for fast and accurate calculation of the integration. It is noted that the current backcalculation project is a continuous work based on our previous forward calculation one. In the forward calculation, we have successfully developed the software *MultiSmart3D* which integrated the Fortran kernel code of forward calculation into the GUI C++ code. Here, in the *BackGenetic3D* program, a similar procedure is applied with the difference that the kernel code is now in the C programming language instead of Fortran.

4.4 IMPROVED GENETIC ALGORITHM

The GA is the core part of the backcalculation program. The basic idea of this algorithm is mimicking the process of natural evolution in order to select the superior and eliminate the inferior genes. The nature has its own standard to judge whether a gene is superior or not. In our program, this standard is the fitness value which is calculated from backcalculated and measured deflections and it is highly related to the gene properties. In the program, a user-defined data structure "STRU_GENO_TYPE" (SGT) is constructed containing all the gene properties: layer modulus and thickness, deflections at each sensor, fitness value of each sensor and total fitness value. In the program there are a number (Default 400) of predefined individuals and each of those has an SGT type data structure holding different gene properties. Among these gene properties, layer modulus and thickness belong to the input information and it is predefined in certain range at the beginning of the program. The other gene properties are based on the calculated results. The deflections are calculated by the forward subroutine. The fitness value at each sensor is calculated based on the calculated deflections (or Area values when necessary) and the measured ones. By doing summation of the fitness values over all sensors, the total fitness value can be obtained. Each time when the old generation evolves to a new one, the gene properties of some individuals are changed. This change is not arbitrary but guided by some rules, so we call it evolution which always directs to better generations. The IGA presented here can be summarized into the following steps:

Step 1

Input the measured deflections, layer information, and sensor information.

Step 2

Initialize the genetic algorithm by producing 400 different individuals with the SGT data structure. The layer modulus and thickness values in these individuals should be as diverse as possible but stay inside a certain range to guarantee that the real modulus and thickness values are included.

Step 3

Based on these 400 series of individual information, calculate 400 series of deflections using the forward subroutine. By applying the objective functions, i.e., substituting the current calculated deflections and the observed deflections in the first step into the objective functions, calculate 400 series of fitness values.

Step 4

If the fitness value of a certain individual is small enough, i.e., the convergent condition is satisfied; then the program stops and gene properties of this individual are the backcalculated results.

Step 5

If the fitness value of all individuals is larger than the threshold fitness value, i.e., one of the individuals is not convergent, then the program continues to the next step.

Step 6

If the best fitness value of all individuals continuously falls into a small range, it means the current generation cannot evolve to the better one and the population needs to be adjusted. The adjusting condition is to count the number of this continuity if the number exceeds some value (Default 7). Then the program goes to a subroutine called "Automatic Divide" to adjust the gene values of all individuals; otherwise, the program goes to the next step.

Step 7

Go through GA Select, GA Crossover and GA Mutate to reproduce new generation. Step 3 is repeating until the convergence happens.

Listed below is the detailed explanation to the boxes in the backcalculation flowchart in Fig. 4.1.

Forward Initialize

Assign the default layer information and sensor information. Layer information includes: layer number, layer thickness, layer modulus and Poisson's ratio. Sensor information includes: diameter of the circular load plate, magnitude of the load, number of sensors and sensor coordinates. The measured deflections at each sensor can be entered manually or can be read from the file of FWD tests with .fwd as the file extension.

GA Initialize

Calculate observed area values based on the measured deflection values. Generate initial individuals with a large population (default 400 individuals in the program). Among these 400 sets of gene properties, the objective layer information (Young's modulus and layer thickness) is assumed in certain ranges so that the real modulus and thickness values are included. Other properties including backcalculated deflections and fitness values are initialized to zeros.

Calculate Fitness

For every individual, calculate the deflections of different sensors using forward calculation subroutine to obtain 400 series of area values. Compare the calculated area values with the observed ones and calculate the fitness value. Find the best fitness value among all 400 individuals.

Convergent?

The condition to decide whether to continue the iteration. When the best fitness value is greater than the pre-assumed threshold value, the iteration continues; otherwise, the program converges for output results.

Adjusting?

If the best values for a certain number (default is 7 in the program) of continuous generations are varying in a very small range (i.e., the best fitness values of continuous generations almost don't change), it means that the current population cannot evolve to the better one and need to be adjusted.

Too Many Iterations?

If the iteration number is too much and exceeds the presupposed maximum number (default 1000) while the best fitness value still doesn't converge, the program will stop and the algorithm fails.

Automatic Divide

Adjust the range of modulus and subdivide the range to new intervals. This part is an improvement to the traditional GA. The traditional GA cannot automatically do the internal repartition and needs to manually redefine the initial population when the algorithm doesn't converge. The automatic internal division can dramatically improve the code efficiency.

GA Select

Select the individuals that will be used to reproduce new generations. The selection is based on the fitness values. Individuals with better fitness values have a higher chance to be selected than those with worse fitness values.

GA Crossover

Generate the next generation from those being selected. There are many crossover techniques for different data structures. In the current code, the random linear crossover method is applied. The two new gene properties are interpolated from the two old gene properties. For example, assuming two old and two new gene properties are respectively A_o, B_o and A_n, B_n. One of the weights for interpolation is randomly set as a and the two new gene properties can be expressed as follows:

$$\begin{aligned} A_n &= aA_o + (1-a)B_o \\ B_n &= (1-a)A_o + aB_o \end{aligned} \qquad \text{Eq. (4.1)}$$

GA Mutate

The objective layer properties (modulus and thickness) of a number of individuals are assigned with new initial values. The number is according to a presupposed mutation probability (Default is 0.05 in the program). The purpose is to keep the diversity of the population to avoid the algorithm which would not converge.

4.5 OUTPUT RESULTS

The output information is currently designed to include the properties of the finally elected individual which is an SGT data structure containing the backcalculated modulus and thickness of each layer and the deflections at each sensor. It is noted that the full-field responses such as stress and strain components at any location of the pavement structure could be calculated by using the forward calculation.

CHAPTER 5 OBJECTIVE FUNCTIONS

5.0 INTRODUCTION

The falling weight deflectometer (FWD) has been widely used in nondestructive test of pavement throughout the world and numerous approaches have been proposed for backcalculation of elastic modulus and thickness. Khazanovich *et al* (2001) calculated the layer material properties of rigid pavements using the backcalculation algorithm which is called “Best Fit”. With the help of the software MODCOMP4, Von *et al* (2002) discussed the procedure and steps to backcalculate the layered elastic properties from deflection basin measurements for all LTPP test sections. Alkasawneh (2007) applied the GA to pavement moduli backcalculation. However, there are still many factors that could substantially affect the accuracy of the backcalculation. For example, Stubstad *et al* (2000) reported that in the LTPP database, some FWD deflection sensors were mislocated and these sensors could yield major inaccuracies in backcalculated moduli. FWD calibration errors (Irwin and Richter 2005 and Orr *et al* 2007) and temperature variation (Xu *et al* 2002 and Alkasawneh *et al* 2007b) are also important issues in backcalculation of pavement parameters. These measurement errors may have significant influence on the backcalculation. For example, Irwin *et al* (1989) analyzed the sources of deflection errors and illustrated through a series of examples how random pavement deflection and thickness errors affect backcalculated moduli. Using the backcalculation program MODULUS (Uzan *et al* 1989) to analyze different pavement structures, Jooste *et al* (1998) found that even allowable and small variations in layer thickness could significantly influence the backcalculated moduli.

5.1 MEASUREMENT ERROR ANALYSIS

Deflection measurement errors are generated by adding random errors to the theoretical deflections (Table 5.1) calculated from the elastic layer theory. In our studies, different random errors are algebraically added to the theoretical deflection at each sensor and the result is rounded to the nearest whole micrometer to follow the FWD recording format. We present some definitions in order to investigate the influence of the measurement errors on backcalculation. These definitions are useful in understanding the measurement errors and the importance of the objective functions in backcalculation method. The following assumptions can be made in the analysis of measurement errors; some of which are similar to Stubstad *et al* (2000).

Assumption 1

For convenience, we assume that the measurement error ε_i of sensor i can be divided into two parts: systematic error ε_i^s and random error ε_i^r. The measured deflection at sensor i, d_i^m, can be written as:

$$\begin{aligned} d_i^m &= d_i^t + \varepsilon_i \\ &= d_i^t + (\varepsilon_i^s + \varepsilon_i^r) \\ &= d_i^t(1+e_i^s) + \varepsilon_i^r \\ &= d_i^t(1+e_i^s+e_i^r) \\ &= d_i^t(1+e_i) \end{aligned} \quad \text{Eq. (5.1)}$$

where d_i^t denotes the theoretical deflection at sensor i, e_i^s $(=\varepsilon_i^s / d_i^t)$ is the relative systematic error, e_i^r $(=\varepsilon_i^r / d_i^t)$ is the relative random error, and e_i $(=e_i^s + e_i^r)$ is the combination of the relative systematic and random errors. In the analysis below, we use the relative systematic error e_i^s and random error ε_i^r as in the expression:

$$d_i^m = d_i^t(1+e_i^s) + \varepsilon_i^r \quad \text{Eq. (5.2)}$$

Assumption 2

The random error ε_i^r follows a normal distribution with zero mean and shows very small deviation (< 2 μm) as in Stubstad *et al* (2000).

Assumption 3

The relative systematic errors e_i^s at each sensor i are identical. Should the relative systematic error be not the same, we can just move the difference into the random error ε_i^r to satisfy:

$$e^s = e_1^s = \cdots = e_n^s \quad \text{Eq. (5.3)}$$

where n denotes the number of sensors in the FWD.

Assumption 4

The center deflection of FWD d_1^m is more reliable than others because of the following reasons:

1. The deflection at different sensors, d_i^m, meets the following inequality:

$$d_i^m > d_{i+1}^m \quad (i = 1, 2, \ldots, n) \quad \text{Eq. (5.4)}$$

2. All random errors, ε_i^r, are very small according to *Assumption* 2;

3. All relative systematic errors, e_i^s , are identical according to *Assumption* 3.

5.2 PROPOSED OBJECTIVE FUNCTIONS

Root mean square (RMS) is the most frequently used objective function in the backcalculation method. We consider this function as well as a new one called area value with correction factor (AVCF). The following sections describe each of these objective functions.

5.2.1 ROOT MEAN SQUARE (RMS)

Based on the deflections, a commonly used goodness-of-fit function in existing backcalculation procedures is the root mean square (RMS).

$$F_{RMS} = \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{d_i^c - d_i^m}{d_i^m} \right)^2 \right]^{1/2} \qquad \text{Eq. (5.5)}$$

where d_i^c is the backcalculated deflection at sensor *i*. According to Eq. (5.5), one advantage of using the RMS in backcalculation procedure is its simplicity. More importantly, when all deflections d_i^m are measured exactly, Eq. (5.5) works perfectly, which means that the calculated deflections are exactly the same as the measured deflections. Through various numerical experiments, we found that the backcalculated results based on RMS are very sensitive to the measurement errors. In other words, even a slight change in measured deflections can result in a dramatic variation in backcalculated layer moduli. This can be clearly seen from the following analysis.

To find the contribution of the measurement errors in backcalculation, let us assume that the theoretical moduli and thickness are used for the calculation of d_i^c so that the backcalculated d_i^c equals the theoretical d_i^t at any given sensor *i*. Then it is easy to obtain

$$\begin{aligned} Min\ F_{RMS} &= \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{d_i^c - d_i^t(1+e_i)}{d_i^t(1+e_i)} \right)^2 \right]^{1/2} \\ &= \left[\frac{1}{n} \sum_{i=1}^{n} \left(\frac{e_i}{1+e_i} \right)^2 \right]^{1/2} \end{aligned} \qquad \text{Eq. (5.6)}$$

Clearly, the relative error of every sensor works equally in the backcalculation procedure, and neither the systematic error nor the random error is weakened or eliminated. This is why the

RMS result is sensitive to errors. Since RMS is unable to treat the measurement errors, we therefore propose a new objective function which can handle the errors, as presented in the next section.

5.2.2 AREA VALUE WITH CORRECTION FACTOR (AVCF)

According to Pierce (1999), the "area" value represents the normalized area of a slice which means the area divided by the deflection measured at the center of the test load d_1. To generalize the area value, we define the area value A_k of the first k sensors as:

$$A_k = \frac{\sum_{i=1}^{k-1}(d_i + d_{i+1})(r_{i+1} - r_i)}{2d_1}, \quad (k \le n) \qquad \text{Eq. (5.7)}$$

where d_i denotes the deflection at sensor i and r_i is the distance between load center and sensor i. In order to consider the error at each sensor, we define a new objective function called area value with correction factor (AVCF).

$$F_{AVCF} = \left\{ \frac{1}{n-1} \sum_{k=1}^{n-1} \left(\frac{A_k^c - A_k^m}{A_k^m} \right)^2 \right\}^{1/2} + \left| \frac{d_1^c - d_1^m}{d_1^m} \right| \qquad \text{Eq. (5.8)}$$

where A_k^c and A_k^m are, respectively, the backcalculated and measured areas. The first term in Eq. (5.8) not only eliminates the systematic errors and weakens the random errors, but also gives full consideration to the deviation at each sensor. The second term works like a correction factor which can adjust the backcalculated deflection close to the measured value. It is noted that if the calculated deflection at the center equals the measured value, the second term in Eq. (5.8) equals zero. Therefore, Eq. (5.8) is superior in handling measurement errors as compared to Eq. (5.5). This function can also make the backcalculated result close to the measured value, independent of the backcalculation algorithm used.

In order to understand how the errors are weakened or eliminated in AVCF function, we replace the calculated deflection with the theoretical one while expressing the formula in terms of the relative error. The area term in the first part of Eq. (5.8) can be rewritten as:

$$\left|\frac{A_k^c - A_k^m}{A_k^m}\right| = \left|\sum_{i=1}^{n} \Psi_i\right| \quad \text{Eq. (5.9)}$$

where

$$\Psi_i = \frac{d_i^t\left(e_1^r - e_i^r\right)\left(r_{i+1} - r_{i-1}\right)}{\Delta} \quad \text{Eq. (5.10)}$$

We denote

$$\begin{aligned}\Delta &= \sum_{j=1}^{n-1}\left[d_j^t\left(1+e_j\right) + d_{j+1}^t\left(1+e_{j+1}\right)\right]\left(r_{j+1} - r_j\right) \\ &= \sum_{j=1}^{n-1}\left[d_j^m + d_{j+1}^m\right]\left(r_{j+1} - r_j\right)\end{aligned} \quad \text{Eq. (5.11)}$$

which states that Δ is a constant depending only on the measurement data. It is shown in Eqs. (5.9) and (5.10) that all relative systematic errors e^s are eliminated and that the relative random error e_i^r at each sensor i is also weakened by subtracting from e_1^r and dividing a constant. However, this analysis is based on the assumption that the measurement error can be divided into systematic and random error which is practically impossible. Furthermore, because all errors are calculated by only one absolute monomial in Eq. (5.9), large individual positive and negative errors cannot be detected. In other words, the function in Eq. (5.9) can still be very small even when large individual errors exist.

5.3 THE PROPOSED ANALYSIS APPROACH

5.3.1 GENETIC ALGORITHM

Genetic algorithms (GAs) are robust and randomized search algorithms based on the evolution theory and natural genetics (Goldberg 1989). These algorithms are used to generate useful solutions to optimization. Alkasawneh (2007) introduced different steps in GA originally established by Mitchell (1999). In this work, we use an improved genetic algorithm (IGA) to backcalculate the elastic modulus and thickness. Fig. 4.1 shows the main components of the IGA and the sequence of the components.

5.3.2 GENERATION OF A PERTURBED DEFLECTIONS

We use *MultiSmart3D* program designed by the Computer Modeling and Simulation (CMS) group at The University of Akron to calculate the surface responses d_i^t at sensor *i* for the given layer moduli, Poisson's ratios, and thicknesses. In order to simulate the measured deflections with errors d_i^m, we perturb the theoretical deflection d_i^t 40 times by adding an error term (Eq. 5.2), which include systematic and random errors. Here the relative systematic errors e^s are given by a uniform distribution generator with the accuracy within ± 8 percent, whilst the random errors ε_i^r are provided by a normal distribution generator with zero mean and 2μ deviations.

5.3.3 BACKCALCULATION BASED ON THE PERTURBED DEFLECTIONS

With fixed Poisson's ratios, backcalculation of layer elastic modulus and thickness is performed by using the perturbed deflections as input. Two objective functions RMS and AVCF are used here. In order to illustrate the performance of the two objective functions, we have calculated the error and standard derivations of the backcalculated layer modulus and thickness for a one-layer pavement over a halfspace. The results will be presented in Chapter 8.

5.4 RMS VS AVCF

The backcalculation of elastic moduli is commonly carried out by assuming a set of pavement-layer moduli (seed moduli) that can produce a deflection basin similar to the measured one from the FWD test. In order to minimize the error between the measured and calculated deflections, the relative root-mean-square error (RMSE) is used to control the convergence of the backcalculated deflections and to assess the acceptance and rejection of the final set of pavement moduli.

The root mean square (RMS) is one of the objective functions incorporated in the *BackGenetic3D* program. Besides this commonly used objective function in backcalculation methods, another objective function called area value with correction factors (AVCF) is also proposed by Computer Modeling and Simulation (CMS) group at The University of Akron to improve the backcalculation in *BackGenetic3D*. These two objective functions are defined by Eqs. (5.5) and (5.8).

The RMSE is usually presented in percentage to show the accuracy of the backcalculation. In the analysis of long-term pavement performance (LTPP) test sections, an RMSE of 3% was used as an acceptable error (Von Quintus and Simpson, 2002). Von Quintus and Simpson, (2002) indicated that, in general, an RMSE value less than 3% has little effect on the average backcalculated elastic moduli. In practice, RMSE values larger than 1% (but less than 3%) can be achieved quickly (Harichandran *et al* 1993). Therefore, the most commonly used value for the RMSE is between 1% and 3%. However, it is believed that achieving a lower RMSE will always enhance the backcalculated elastic moduli and therefore more accurate results can be obtained. The effect of the backcalculated elastic moduli and the associated RMSE on the strain and stress response in flexible pavements was investigated using a three-layer pavement section by Alkasawneh *et al* (2007).

In general, RMS is a commonly used goodness-of-fit function in existing backcalculation procedures. However, backcalculated results based on RMS are very sensitive to the measurement errors. It means that even a slight change in measured deflections can result in a dramatic variation in backcalculated layer moduli. On the other hand, AVCF can make the backcalculated result close to the measured value independent of the backcalculation algorithm used. While RMS is sensitive to measurement errors, AVCF is found to be very accurate even when measurement errors exist. Thus, this new objective function AVCF could be remarkably helpful in future backcalculation of pavement properties. In the following section, we present some typical numerical examples of real pavement structures in order to illustrate the importance of the objective functions in backcalculation.

CHAPTER 6 BACKGENETIC3D PROGRAM

6.0 INTRODUCTION

The idea of evolutionary computing was introduced in the 1960s by I. Rechenberg in his work called "Evolution strategies" (Evolutionsstrategie in original). Other researchers developed his idea from time to time. In 1975, John Holland and his colleagues published the book "Adaption in Natural and Artificial Systems" and defined a new topic called genetic algorithms (GAs). This method which is substantially popularized by David Goldberg in 1989 is a search technique in computer science to find an approximate solution for problems. This algorithm uses bio-based techniques and has been inspired by Darwin's theory of evolution. There are different types of search techniques in computer science (Fig. 6.1). A simple procedure of the GA usually contains an initialization step, a loop, and the output results. The crossover and mutation are the most important parts in GA. Genetic algorithms belong to the larger class of evolutionary algorithms (EAs), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. The *Backgenetic3D* program is a user-friendly windows-based one which uses the improved GA to backcalculate the elastic modulus and thickness in pavement engineering. This chapter describes the features of this program and how it is applied to the problems in pavement engineering.

6.1 THEORY OF BACKGENETIC3D

6.1.1 SEARCH TECHNIQUES

Figure 6.1 shows the algorithm of different classes of search techniques. It is noted the GA is an evolutionary algorithm in guided random search techniques that contrast from calculus-based and enumerative techniques. A simple procedure in GA is shown in Fig. 6.2. Complete explanation of each step has already been presented in Section 4.4.

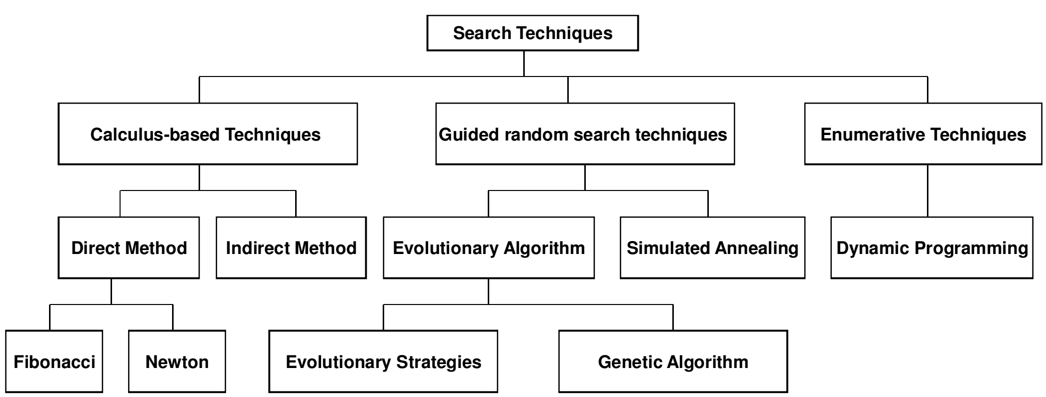


Figure 6.1 Classes of search techniques in computer science.

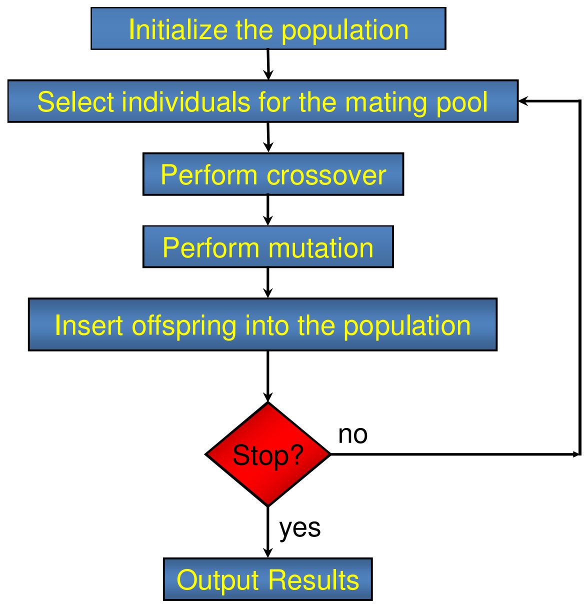


Figure 6.2 Simple procedure of genetic algorithm.

6.1.2 LIMITATIONS OF CLASSICAL METHODS FOR BACKCALCULATION

The classical methods for moduli backcalculation have several limitations. None of the existing classical backcalculation methods can find the “actual” pavement moduli due to the theoretical limitations of the existing methods. The thickness and elastic modulus of pavement with too many layers are assumed to be equivalent to the first layer in classical methods. Thus, it always needs to be modified by a correction factor that is dependent on the pavement system. The gradient relaxation method is based on solving a set of simultaneous equations. In this method the total number of layers is limited to 20 layers and there is no guarantee that convergence happens. In direct interpolation method a database has been created that contains solutions for different loading configurations and geometries. This method is also limited to maximum 20 layers and it is not correctly applicable for new experimental cases.

6.1.3 MERITS OF GENETIC ALGORITHM

To overcome the limitations of classical methods for backcalculation, the GA has been considered by The University of Akron team. The most important advantages of GA are:

- There is no need to compute any form of derivatives in it, which can avoid computationally expensive derivative calculations.

- This method works well with both continuous and discrete parameters.
- It is possible to do simultaneous searches from a wide variety of sampling.
- Using the GA, it is possible to deal with a large number of parameters easily and hence this method is well suited for parallel computers.

GA provides a list of optimum solutions in comparison with classical methods that involve a single solution.

6.1.4 GENETIC ALGORITHM IN PAVEMENT ENGINEERING

The use of GA in pavement engineering is relatively new and no guidelines or thorough investigations have been carried out to address all aspects and challenges associated with the backcalculation procedure using this algorithm. To use the GA in pavement engineering, we can substitute modulus of elasticity as the x and y chromosomes. The chromosomes are the most important part of the structure of a cell. Genetic information is stored in the chromosomes and each chromosome is built of DNA. The chromosome is divided into numerous parts called genes. The most prominent use of GA in pavement engineering can be found in Fwa *et al* (1997), Kameyama *et al* (1998), Reddy *et al* (2004), Tsai *et al* (2004), and Alkasawneh (2007).

6.1.5 LIMITATIONS OF BACKCALCULATION USING GENETIC ALGORITHM

Despite the varieties of useful advantages of the GA in calculations of layer moduli and thicknesses, it has some limitations. The GA increases the processing time for calculations which makes it only for limited number of output points and limited number of layers. Also, there is no suitable forward calculation in GA. The range of seed values is important in backcalculation by GA. Large seed range for moduli or thickness in backcalculation may result in a solution away from the best solution for each layer. On the other hand, small range of seed values may limit the GA to find the correct solution and in such a case the results could be close to either the maximum or minimum seed values. The current backcalculation program does not account for temperature gradient in asphalt concrete. Further research is necessary to evaluate the GA-based backcalculation with thermal analysis and to find out the capability of this GA-based method. In general, the backcalculation based on GA is time consuming since it needs to search a large pool of data and optimize the result in a step-by-step procedure. This limitation will rise by increasing the number of pavement layers and decreasing the error tolerance in objective functions.

6.2 BACKGENETIC3D SOFTWARE

In our backcalculation of pavement layer moduli and thicknesses, we use the most efficient forward program *MultiSmart3D*. *MultiSmart3D* software is developed by the group of Computer Modeling and Simulation at the University of Akron under the sponsorship of ODOT/FHWA. The core code of the *MultiSmart3D* was programmed in Fortran, and the user-friendly executive program was generated by incorporating core code into Microsoft Visual C++ (VC++).

The procedure to determine modulus of elasticity for pavement materials using measured surface deflections is generally called backcalculation. According to Irwin *et al* (1989), backcalculation is popular today because of three important advances in the field of engineering.

1. The realization that strong pavements have small deflections and weak pavements have large deflections, and hence pavement performance may be related to deflection.
2. The development of mechanistic theories that relates fundamental material properties to the stresses, strains, and deflections in a layered system.
3. The development of portable, accurate, and affordable instrumentation systems for measuring pavement deflections.

The advent of high-speed digital computers made it possible to accomplish the required computation in a reasonable amount of time.

By combining *Multismart3D* with the improved GA for backcalculation, a new user-friendly program called *BackGenetic3D* is designed by the group of Computer Modeling and Simulation at The University of Akron. This program is able to backcalculate the elastic modulus and thickness of a layered pavement with any number of layers.

6.2.1 BACKGENETIC3D GRAPHICAL USER INTERFACE (GUI)

By using the *MultiSmart3D* software for forward computation and utilizing the improved GA as a search engine, we designed a software product that can be used for backcalculation of pavement layer moduli and thicknesses. It is advised that the software can be easily useful if it is presented in the form of a graphical user interface (GUI). The *BackGenetic3D* program has been designed as a GUI using Microsoft Visual C++ which is user-friendly, Windows-based, and simple.

6.2.2 BACKGENETIC3D CONTENT

The *BackGenetic3D* GUI involves a main window, four information dialogs, and a menu bar. The first dialog is called *General Information*. In this window the general conditions can be defined for the software. Several user-friendly list boxes are used to cover all the conditions. The conditions are divided into two sections consisting of the initial and thermo conditions. The conditions that are defined for *BackGenetic3D* GUI are as follows.

- Units
    1. SI Units
    2. US Units
- Case
    1. Pure elastic
    2. Thermoelastic
- Boundary condition
    1. Halfspace
    2. Rigid body foundation
- Surface thermo type
    1. Temperature
    2. Heat flux
- Surface thermo value
- Bottom thermo type
    1. Temperature
    2. Heat flux
- Bottom thermo value

It is noted that the thermo-related part is not available but is intended to be added in the future. The second dialog in the GUI is designed to input the initial values for the calculation and is called *Initial Information* dialog. *Sensor Information* is the third dialog employed to provide the information for different sensors. The last dialog is called *Objective Function* and the user can select which objective function to use for calculations.

The execution of the program is initiated using the defined menu bar at the top of the GUI. A detailed explanation of the GUI will be described in the tutorial section at the end of this chapter. The format of the output files is described in Section 6.5.2.

6.2.3 INPUT AND OUTPUT IN BACKGENETIC3D

In general, the input information in *BackGenetic3D* consists of two different inputs since the software is based on the forward calculation in *MultiSmart3D* and the improved GA.

FWD Inputs:

- Poisson’s ratio for each layer

- Measured deflections
- Location of measured deflections
- Loading geometry
- Load magnitude
- Elastic modulus range and thickness range of each layer

GA Inputs:

- Population size
- Number of generations
- Jump mutation probability
- Creep mutation probability
- Crossover probability
- Number of children (1 or 2)
- Chromosome length
- Elitism option (yes or no)
- Niching option (yes or no)
- Saving the chromosomes of the best solution (yes or no)

Also there are several output results from the *BackGenetic3D* GUI which are summarized here.

BackGenetic3D Output:

- Backcalculated elastic modulus and thickness of each individual (chromosome)
- Fitness of backcalculated moduli and thicknesses
- Best fitness in each population (generation)
- Average elastic modulus and thickness of each generation for each layer
- Average fitness of each generation
- Number of crossover
- Number of mutations
- Total time of backcalculation

6.3 BACKGENETIC3D SUBROUTINES

In *BackGenetic3D* program, the code was written in C++ with a DLL connection to forward and backward calculation in C programming language. In the code of the *BackGenetic3D* program several subroutines are designed to improve the application of the program. These subroutines are divided into three major sections. The complete description of those subroutines is presented in Appendix G.

6.4 BACKGENETIC3D INITIAL PARAMETERS

The values of initial parameters in *BackGenetic3D* program is defined in Appendix H. These parameters are either a part of the basic calculations such as the number of pavement layers or a predefined parameter in forward/backward calculations.

6.5 DEVELOPMENT OF THE BACKGENETIC3D GUI

The structure of the *BackGenetic3D* GUI was improved during the time since the project started years ago. According to the recommendations and discussions from the meetings with ODOT, several improvements have been made to the content and dialogs of the program and certain improvements on the algorithm have been achieved during this phase of studies. Figure 6.3 illustrates the general flowchart of the *BackGenetic3D* program and Figure 6.4 shows the flowchart on the recent development of the *BackGenetic3D* GUI. The running section of the code has already been structured in the C program and the connection between C and C++ environments has been extended for considering several stations in the pavement analysis.

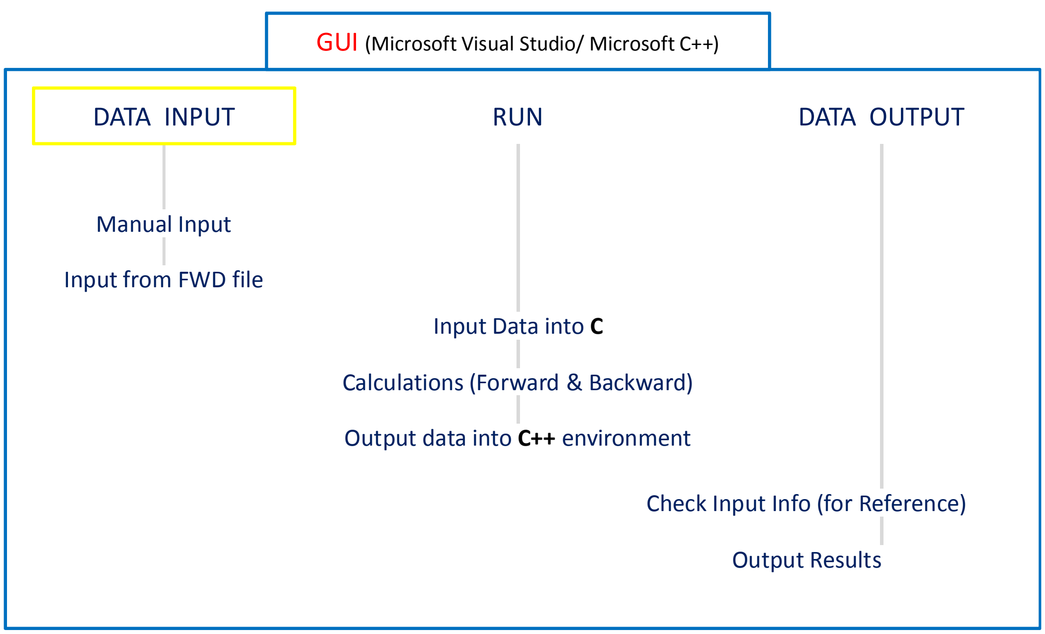


Figure 6.3 The general flowchart of the *BackGenetic3D* program.

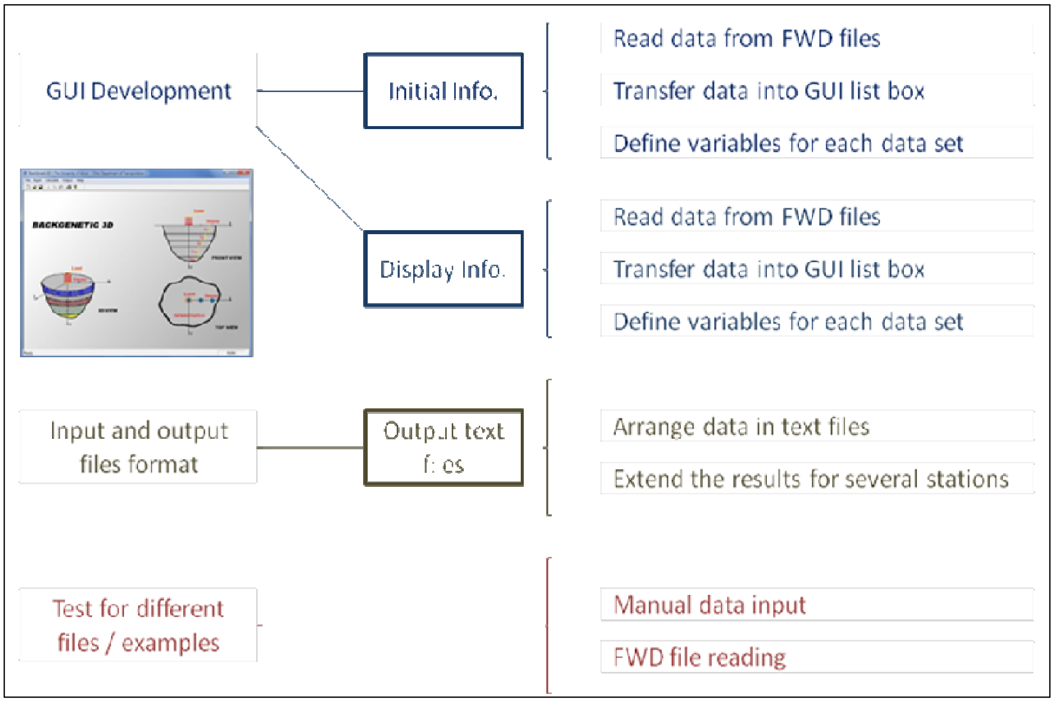
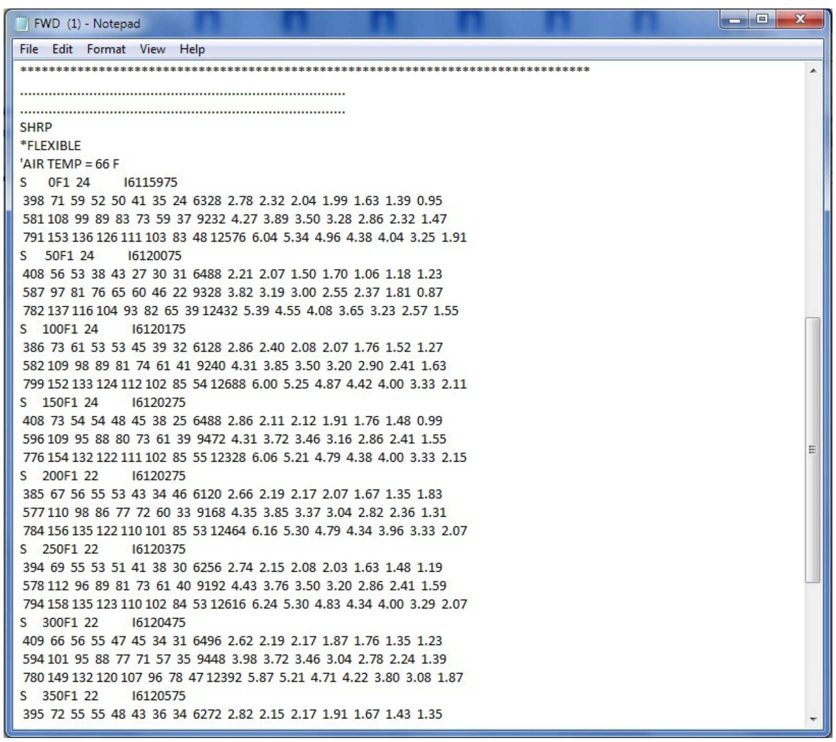


Figure 6.4 The flowchart of the most recent *BackGenetic3D* GUI.



```
FWD (1) - Notepad
File Edit Format View Help
*****************************************************************************
.........................................................................
.........................................................................
SHRP
*FLEXIBLE
'AIR TEMP = 66 F
S     0F1  24        I6115975
 398  71  59  52  50  41  35  24  6328 2.78 2.32 2.04 1.99 1.63 1.39 0.95
 581 108  99  89  83  73  59  37  9232 4.27 3.89 3.50 3.28 2.86 2.32 1.47
 791 153 136 126 111 103  83  48 12576 6.04 5.34 4.96 4.38 4.04 3.25 1.91
S    50F1  24        I6120075
 408  56  53  38  43  27  30  31  6488 2.21 2.07 1.50 1.70 1.06 1.18 1.23
 587  97  81  76  65  60  46  22  9328 3.82 3.19 3.00 2.55 2.37 1.81 0.87
 782 137 116 104  93  82  65  39 12432 5.39 4.55 4.08 3.65 3.23 2.57 1.55
S   100F1  24        I6120175
 386  73  61  53  53  45  39  32  6128 2.86 2.40 2.08 2.07 1.76 1.52 1.27
 582 109  98  89  81  74  61  41  9240 4.31 3.85 3.50 3.20 2.90 2.41 1.63
 799 152 133 124 112 102  85  54 12688 6.00 5.25 4.87 4.42 4.00 3.33 2.11
S   150F1  24        I6120275
 408  73  54  54  48  45  38  25  6488 2.86 2.11 2.12 1.91 1.76 1.48 0.99
 596 109  95  88  80  73  61  39  9472 4.31 3.72 3.46 3.16 2.86 2.41 1.55
 776 154 132 122 111 102  85  55 12328 6.06 5.21 4.79 4.38 4.00 3.33 2.15
S   200F1  22        I6120275
 385  67  56  55  53  43  34  46  6120 2.66 2.19 2.17 2.07 1.67 1.35 1.83
 577 110  98  86  77  72  60  33  9168 4.35 3.85 3.37 3.04 2.82 2.36 1.31
 784 156 135 122 110 101  85  53 12464 6.16 5.30 4.79 4.34 3.96 3.33 2.07
S   250F1  22        I6120375
 394  69  55  53  51  41  38  30  6256 2.74 2.15 2.08 2.03 1.63 1.48 1.19
 578 112  96  89  81  73  61  40  9192 4.43 3.76 3.50 3.20 2.86 2.41 1.59
 794 158 135 123 110 102  84  53 12616 6.24 5.30 4.83 4.34 4.00 3.29 2.07
S   300F1  22        I6120475
 409  66  56  55  47  45  34  31  6496 2.62 2.19 2.17 1.87 1.76 1.35 1.23
 594 101  95  88  77  71  57  35  9448 3.98 3.72 3.46 3.04 2.78 2.24 1.39
 780 149 132 120 107  96  78  47 12392 5.87 5.21 4.71 4.22 3.80 3.08 1.87
S   350F1  22        I6120575
 395  72  55  55  48  43  36  34  6272 2.82 2.15 2.17 1.91 1.67 1.43 1.35
```

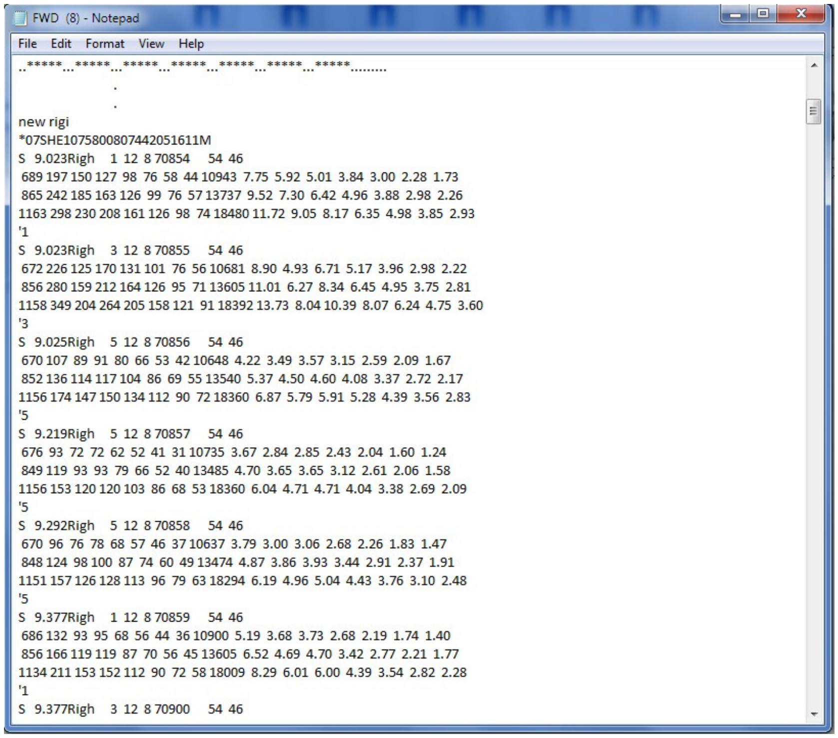
Figure 6.5 The data set section of FWD file 1.

6.5.1 DATA READING FROM FWD FILE

In order to design an accurate, convenient, handy, and applicable GUI program, the program is designed to be able to receive the FWD input information both manually and from predefined files. The FWD files are the format of the files from the FWD machines. Figures 6.5 and 6.6 illustrate the information in two typical FWD files. There is certain information in the FWD file provided from the standard test of the FWD machine. Some of the data in an FWD file could be directly or indirectly considered in *BackGenetic3D* and/or in backcalculation operations. Each FWD file contains the header information of 36 lines, followed by test data and comments. Figure 6.7 illustrates the *header* section of a typical FWD file. The first line contains the letter "R" meaning random type of a file, and also the test date and the name of the file. Figure 6.8 shows the file name and test date in a header section of an FWD file. The first character in line 2 (number "7" in Fig. 6.7) means the number of deflectors which is equal to the number of sensors. Line 3 contains the radius of the plate in *mm* at the beginning of the line followed by the distance of each sensor from the load center in *mm*. The rest of the data in that line are the values of the same load radius and distances in US unit *inch*. Line 4 shows the working disk drive and directory that the file is saved and in line 5 there is information on location and route of the test. The *header* section is complete at the end of line 36. Figure 6.9 illustrates the *data set* section of a typical FWD file. The letter "S" stands for station and the line after that contains the load magnitude in *kPa* and measured deflection at each sensor in *micron* followed by the corresponding US units *lbf* and *mil* (one thousandth of an inch).

There are some minor differences in old and new FWD files that could be very important in data reading in the *BackGenetic3D* program. The three cases for *Distance from load center* are presented in Table 6.1 to differentiate the old and new FWD files. The best choice is to read the information from an FWD file line by line to be able to avoid any inconsistence when the FWD file is examined.

The normalized measured deflections for three different types of pavements are plotted in Fig. 6.10-12. In each diagram, the recorded deflection is divided by the applied load to make it normalized and be comparable to other data set of loads and deflections. For all three types of pavements, there are slight deviations in each load. Based on these diagrams, the mean values can be used instead of the three sets of loads and deflections data from each station. For flexible pavement, the deviation from the mean value at the first drop is more sensible than the other two drops. However, the mean values are still close to the values from the other two drops. Therefore, the magnitude for all three loads and deflections are read by the program at first and then the mean values are used in backcalculation.



FWD (8) - Notepad

File Edit Format View Help

```
..*****...*****...*****...*****...*****...*****...*****.........
                 .
                 .
new rigi
*07SHE1075800807442051611M
S  9.023Righ   1 12 8 70854    54 46
 689 197 150 127 98 76 58 44 10943 7.75 5.92 5.01 3.84 3.00 2.28 1.73
 865 242 185 163 126 99 76 57 13737 9.52 7.30 6.42 4.96 3.88 2.98 2.26
1163 298 230 208 161 126 98 74 18480 11.72 9.05 8.17 6.35 4.98 3.85 2.93
'1
S  9.023Righ   3 12 8 70855    54 46
 672 226 125 170 131 101 76 56 10681 8.90 4.93 6.71 5.17 3.96 2.98 2.22
 856 280 159 212 164 126 95 71 13605 11.01 6.27 8.34 6.45 4.95 3.75 2.81
1158 349 204 264 205 158 121 91 18392 13.73 8.04 10.39 8.07 6.24 4.75 3.60
'3
S  9.025Righ   5 12 8 70856    54 46
 670 107 89 91 80 66 53 42 10648 4.22 3.49 3.57 3.15 2.59 2.09 1.67
 852 136 114 117 104 86 69 55 13540 5.37 4.50 4.60 4.08 3.37 2.72 2.17
1156 174 147 150 134 112 90 72 18360 6.87 5.79 5.91 5.28 4.39 3.56 2.83
'5
S  9.219Righ   5 12 8 70857    54 46
 676 93 72 72 62 52 41 31 10735 3.67 2.84 2.85 2.43 2.04 1.60 1.24
 849 119 93 93 79 66 52 40 13485 4.70 3.65 3.65 3.12 2.61 2.06 1.58
1156 153 120 120 103 86 68 53 18360 6.04 4.71 4.71 4.04 3.38 2.69 2.09
'5
S  9.292Righ   5 12 8 70858    54 46
 670 96 76 78 68 57 46 37 10637 3.79 3.00 3.06 2.68 2.26 1.83 1.47
 848 124 98 100 87 74 60 49 13474 4.87 3.86 3.93 3.44 2.91 2.37 1.91
1151 157 126 128 113 96 79 63 18294 6.19 4.96 5.04 4.43 3.76 3.10 2.48
'5
S  9.377Righ   1 12 8 70859    54 46
 686 132 93 95 68 56 44 36 10900 5.19 3.68 3.73 2.68 2.19 1.74 1.40
 856 166 119 119 87 70 56 45 13605 6.52 4.69 4.70 3.42 2.77 2.21 1.77
1134 211 153 152 112 90 72 58 18009 8.29 6.01 6.00 4.39 3.54 2.82 2.28
'1
S  9.377Righ   3 12 8 70900    54 46
```

Figure 6.6 The data set section of FWD file 2.

```
R80        201105177507511A36F20
70      08002-355 60000  00  60 .
 150    0-305 305 610 91412191524  5.91  0.00-12.00 12.00 24.00 36.00 48.00 60.00
W:\FWD Data\FWD 2011\4-Lane .FWD
SHE 75
S
S
                 16.802  17.765
 8.015.0 3.510.0 3.020.0 3.010.0
Ld   950 1.011  65.0           .
D1  7331 0.997 1.012           .
D2  7332 1.000 1.011           .
D3  7333 1.001 0.980           .
D4  7335 0.995 1.008           .
D5  7336 1.002 0.999           .
D6  7337 0.999 1.010           .
D7  7338 0.990 1.021           .
D* N0    1.000 1.000           .
D* N0    1.000 1.000           .
D* N0    1.000 1.000           .

11   7   1110 1 1              .
   5 2.0   2 2.0
*07SHE1075800807442051611M
DtCty PxNnnnS 000+0.0 000+0.0 St
  Cty P Nnnn
000+0.0 000+0.0 St ...
 300   0   0   0   0   0   0   0 11.81  0.00  0.00  0.00  0.00  0.00  0.00  0.00
       0       0       0       0
BB22222PBB22222PBB22222PBB22222PBB22222PBB22222PBB22222S........
BB22222PBB22222PBB22222PBB22222PBB22222PBB22222PBB22222S........
                               .
..*****...*****...*****...*****...*****...*****...*****.........
                               .
```

Figure 6.7 Header section in a typical FWD file.

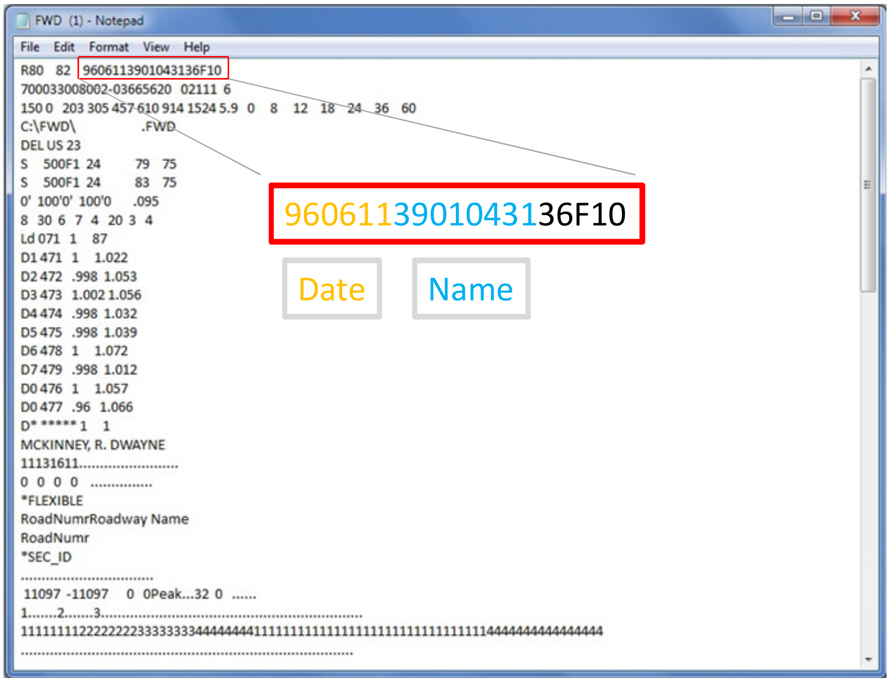


Figure 6.8 File name and test date in an FWD file.

```
          0          0          0          0
BB22222PBB22222PBB22222PBB22222PBB22222PBB22222PBB22222S........
BB22222PBB22222PBB22222PBB22222PBB22222PBB22222PBB22222S........
                                       .
..*****...*****...*****...*****...*****...*****...*****.........
                                       .
                                       .
new rigi
*07SHE1075800807442051611M
S    9.023Righ     1  12   8 70854       54  46
 689 197 150 127  98  76  58  44 10943  7.75  5.92  5.01  3.84  3.00  2.28  1.73
 865 242 185 163 126  99  76  57 13737  9.52  7.30  6.42  4.96  3.88  2.98  2.26
1163 298 230 208 161 126  98  74 18480 11.72  9.05  8.17  6.35  4.98  3.85  2.93
'1
S    9.023Righ     3  12   8 70855       54  46
 672 226 125 170 131 101  76  56 10681  8.90  4.93  6.71  5.17  3.96  2.98  2.22
 856 280 159 212 164 126  95  71 13605 11.01  6.27  8.34  6.45  4.95  3.75  2.81
1158 349 204 264 205 158 121  91 18392 13.73  8.04 10.39  8.07  6.24  4.75  3.60
'3
S    9.025Righ     5  12   8 70856       54  46
 670 107  89  91  80  66  53  42 10648  4.22  3.49  3.57  3.15  2.59  2.09  1.67
 852 136 114 117 104  86  69  55 13540  5.37  4.50  4.60  4.08  3.37  2.72  2.17
1156 174 147 150 134 112  90  72 18360  6.87  5.79  5.91  5.28  4.39  3.56  2.83
'5
S    9.219Righ     5  12   8 70857       54  46
 676  93  72  72  62  52  41  31 10735  3.67  2.84  2.85  2.43  2.04  1.60  1.24
```

Figure 6.9 Data set section in a typical FWD file.

Table 6.1 Distance from the loading center in three different FWD data files

	Distance from load center (*in*)						
Case 1	0	-12	12	24	36	48	60
Case 2	0	8	12	18	24	36	60
Case 3	0	-12	12	18	24	36	60

The format of the FWD file is not always strictly fixed and there are some small modifications during the time to make it more useful in pavement analysis. There are some minor changes in the position in some parts of the file. Therefore the best way to read the information from any FWD file could be line-by-line reading. From the first line in the file, test date and file name is placed from character 14 to 19 and 20 to 27, respectively. In line three, the data for the radius of plate and the distances from the load center were provided. The information for load magnitude and measured deflections was provided in the main section of the FWD files.

The same method of data reading in data set section of FWD files has been extended to all other stations. First of all, the load and deflection from the first station are saved into variables. The average values of the three loads and three deflections in each sensor are calculated in the code and the results are assigned to the corresponding variable in the main GUI code. Then, the stream pointer is placed in the next line and tries to find the character "S". If the character "S" is placed at the beginning of a line, the code will continue to read data from the following line and save the data as loads and deflections for the next station. The same procedure will be continued to the end of the file. Finally the total number of stations in any FWD file can be recorded which is also important in the number of calculations. The reason to read data in this method is the different types of the FWD file. As it can be observed from the end of data set in each station (Figs. 6.5 and 6.6), the line difference between series of stations is not always fixed in the FWD files. Since there is always a character "S" (stands for station) at the beginning of the line and the data information for the next station to start from the line after that, it is an appropriate landmark in any FWD file for data reading.

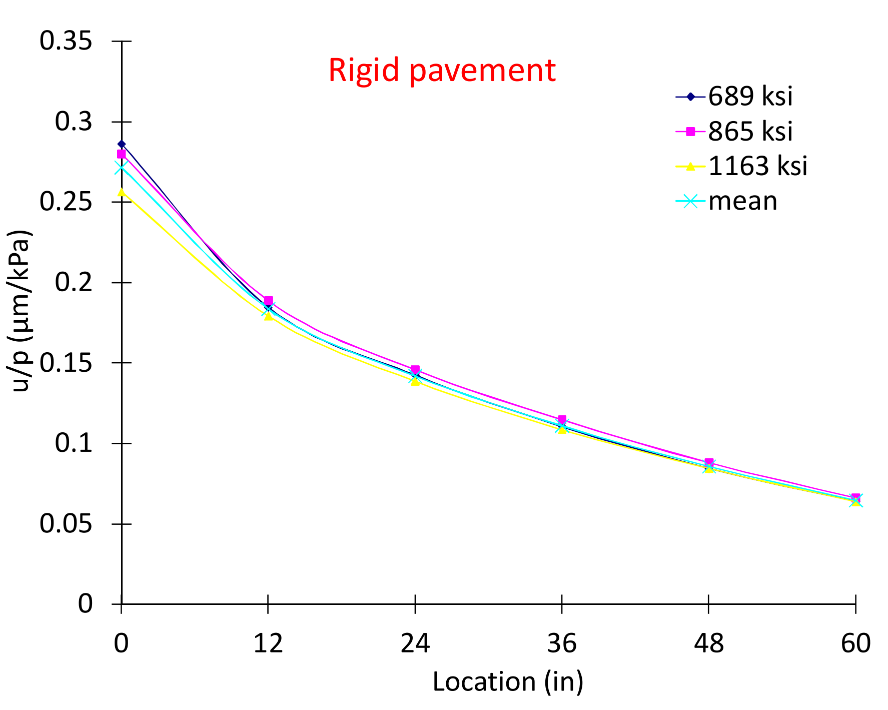


Figure 6.10 Deflection versus distance from load center in a rigid pavement.

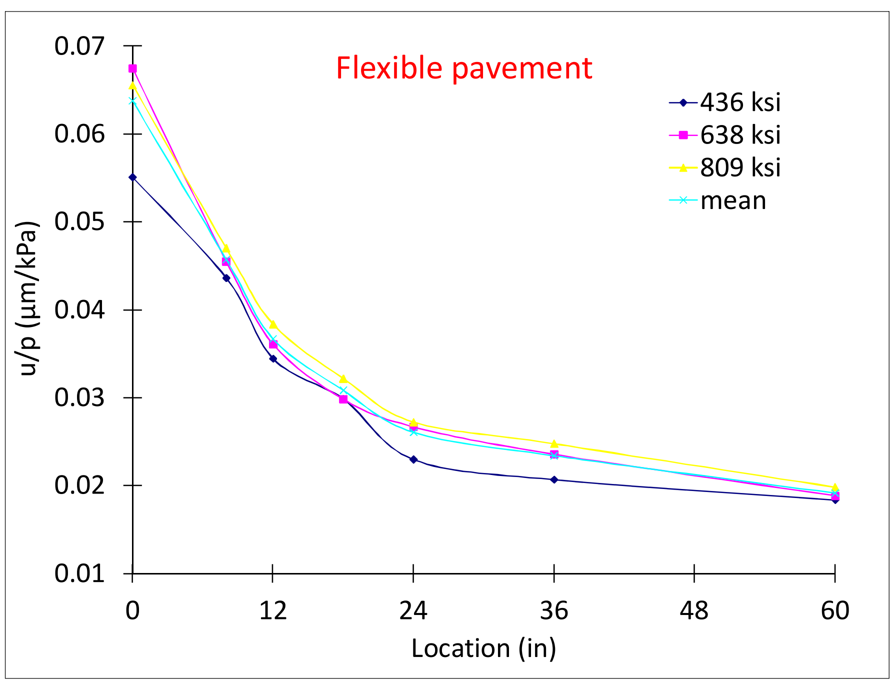


Figure 6.11 Deflection versus distance from load center in a flexible pavement.

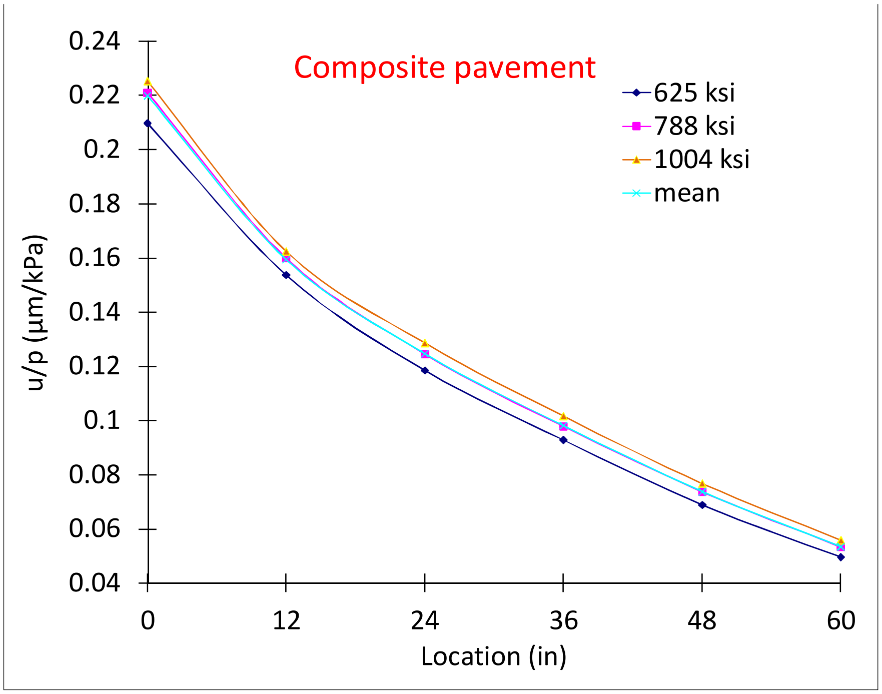


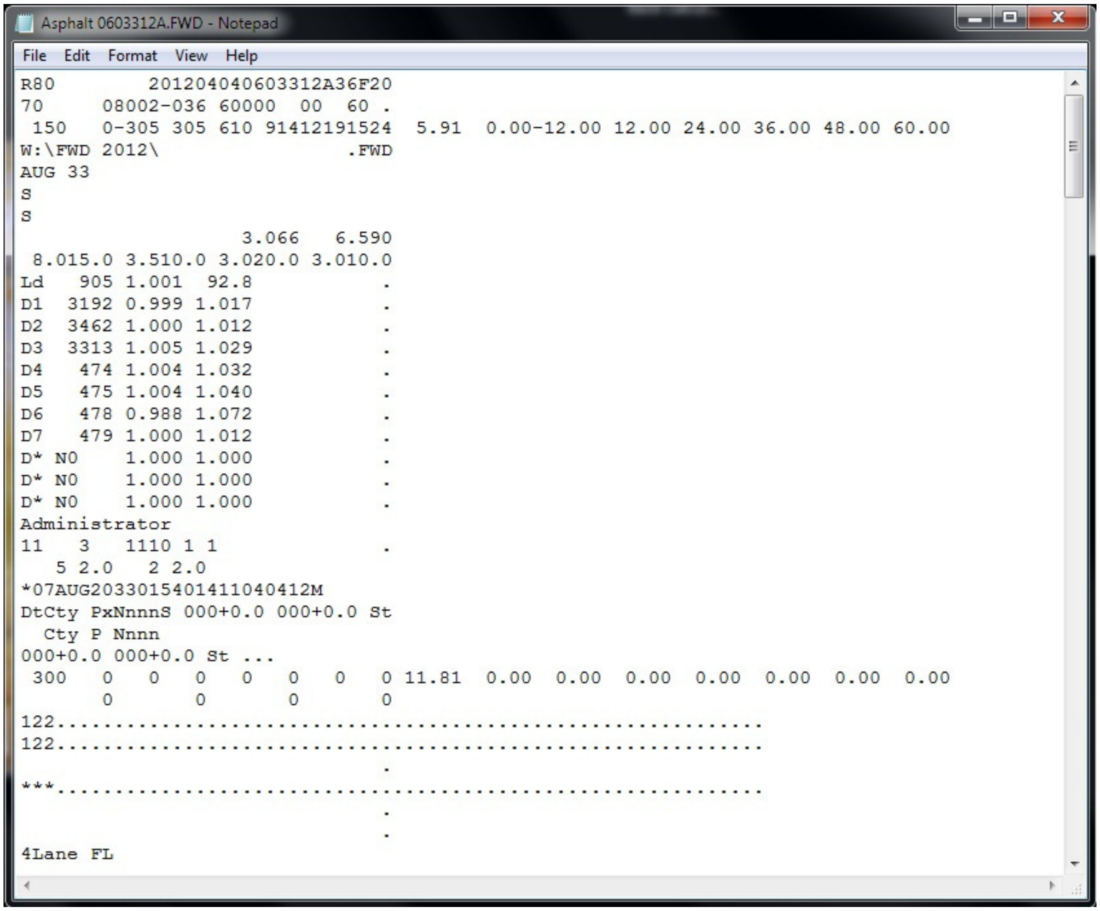
Figure 6.12 Deflection versus distance from load center in a composite pavement.

6.5.2 FORMAT OF THE OUTPUT FILES

The output files including the *Input check* and *Output results* have been modified to make it simple, easy to read, but also comprehensive. Figures 6.13 and 6.14 show the header and data set sections of an FWD file recorded in-situ on April 4, 2012 for a flexible pavement. The *Input check* and *Output results* files are illustrated in Figs. 6.15 and 6.16. As illustrated in these figures, the following parameters are written for each station in the output result file:

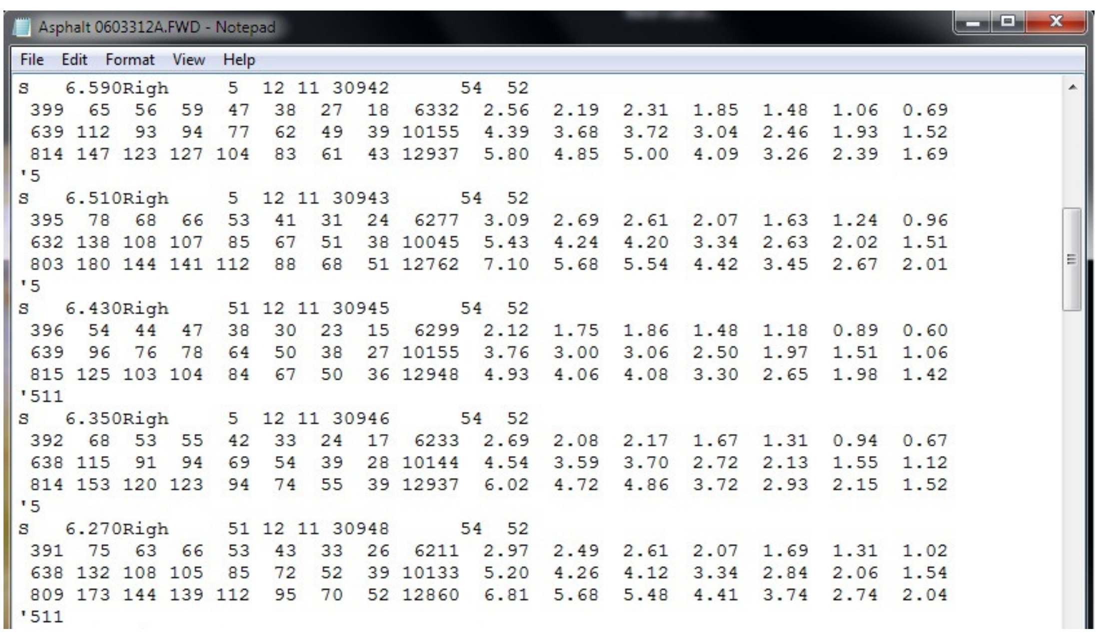
1 Load magnitude (the average of the three loads at each station)
2 Backcalculated elastic modulus for each layer including the halfspace
3 Backcalculated thickness for each layer without the halfspace
4 Calculated deflection at each sensor

Note that the name of the file, the route in the FWD test, the date of the test, and the applied objective function have also been presented in the results for future reference.



```
Asphalt 0603312A.FWD - Notepad
File  Edit  Format  View  Help
R80         201204040603312A36F20
70     08002-036 60000  00   60 .
 150   0-305 305 610 91412191524  5.91  0.00-12.00 12.00 24.00 36.00 48.00 60.00
W:\FWD 2012\                .FWD
AUG 33
S
S
                3.066   6.590
 8.015.0 3.510.0 3.020.0 3.010.0
Ld    905 1.001  92.8           .
D1   3192 0.999 1.017           .
D2   3462 1.000 1.012           .
D3   3313 1.005 1.029           .
D4    474 1.004 1.032           .
D5    475 1.004 1.040           .
D6    478 0.988 1.072           .
D7    479 1.000 1.012           .
D* NO     1.000 1.000           .
D* NO     1.000 1.000           .
D* NO     1.000 1.000           .
Administrator
11   3   1110 1 1               .
   5 2.0    2 2.0
*07AUG2033015401411040412M
DtCty PxNnnnS 000+0.0 000+0.0 St
  Cty P Nnnn
000+0.0 000+0.0 St ...
 300    0    0    0    0    0    0    0 11.81  0.00  0.00  0.00  0.00  0.00  0.00  0.00
        0         0         0         0
122.............................................................
122.............................................................
                                .
***.............................................................
                                .
                                .

4Lane FL
```

Figure 6.13 Header section of an FWD file recorded in-situ on April 4, 2012.



```
Asphalt 0603312A.FWD - Notepad
File  Edit  Format  View  Help
S    6.590Righ     5  12 11 30942       54   52
 399  65  56  59  47  38  27  18  6332  2.56  2.19  2.31  1.85  1.48  1.06  0.69
 639 112  93  94  77  62  49  39 10155  4.39  3.68  3.72  3.04  2.46  1.93  1.52
 814 147 123 127 104  83  61  43 12937  5.80  4.85  5.00  4.09  3.26  2.39  1.69
'5
S    6.510Righ     5  12 11 30943       54   52
 395  78  68  66  53  41  31  24  6277  3.09  2.69  2.61  2.07  1.63  1.24  0.96
 632 138 108 107  85  67  51  38 10045  5.43  4.24  4.20  3.34  2.63  2.02  1.51
 803 180 144 141 112  88  68  51 12762  7.10  5.68  5.54  4.42  3.45  2.67  2.01
'5
S    6.430Righ    51  12 11 30945       54   52
 396  54  44  47  38  30  23  15  6299  2.12  1.75  1.86  1.48  1.18  0.89  0.60
 639  96  76  78  64  50  38  27 10155  3.76  3.00  3.06  2.50  1.97  1.51  1.06
 815 125 103 104  84  67  50  36 12948  4.93  4.06  4.08  3.30  2.65  1.98  1.42
'511
S    6.350Righ     5  12 11 30946       54   52
 392  68  53  55  42  33  24  17  6233  2.69  2.08  2.17  1.67  1.31  0.94  0.67
 638 115  91  94  69  54  39  28 10144  4.54  3.59  3.70  2.72  2.13  1.55  1.12
 814 153 120 123  94  74  55  39 12937  6.02  4.72  4.86  3.72  2.93  2.15  1.52
'5
S    6.270Righ    51  12 11 30948       54   52
 391  75  63  66  53  43  33  26  6211  2.97  2.49  2.61  2.07  1.69  1.31  1.02
 638 132 108 105  85  72  52  39 10133  5.20  4.26  4.12  3.34  2.84  2.06  1.54
 809 173 144 139 112  95  70  52 12860  6.81  5.68  5.48  4.41  3.74  2.74  2.04
'511
```

Figure 6.14 Data set section of an FWD file recorded in-situ on April 4, 2012.

```
INPUT.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Input Check
FWD file: 0603312A    Route: AUG 33           Tested on 2012 04 04
Objective Function: RMS

----------------------------------------------------------------------------
No of Layers:                3
No of Sensors:               6

Plate Radius (in):           5.91
----------------------------------------------------------------------------
Layer No:                    1       2       3       HS

Poisson's Ratio:             0.35    0.30    0.40    0.30

Seed Moduli MIN (ksi):       100     15      7       7
Seed Moduli MAX (ksi):       5,000   700     200     200

Seed Thickness MIN (in):     17.00   9.00    100.00
Seed Thickness MAX (in):     17.00   9.00    100.00
----------------------------------------------------------------------------
Sensor No:                   1       2       3       4       5       6

Sensor Distnace (in):        0.0     12.0    24.0    36.0    48.0    60.0
```

Figure 6.15 Input check for running the program via *BackGenetic3D* using an FWD file on April 4, 2012 for a flexible pavement.

```
Ex 2.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Output Check
FWD file: 0603312A    Route: AUG 33           Tested on 2012 04 04
Objective Function: RMS

SEED Moduli MIN (ksi):           100       15        7         7
SEED Moduli MAX (ksi):         5,000      700      200       200
SEED Thickness MIN (in):       17.00     9.00   100.00
SEED Thickness MAX (in):       17.00     9.00   100.00

---------------------------------------------------------------------------------
Station     6.590Righ
Load Average (lbf):            9,808
Layer No:                          1        2        3        HS
BackCalc. Moduli (ksi):        1,012       38       14       193
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24        36        48        60
Measured Deflection (mil):      4.25     3.68     2.99      2.40      1.79      1.30
Calc. Deflection (mil):         4.33     3.44     2.90      2.41      1.95      1.54
---------------------------------------------------------------------------------
Station     6.510Righ
Load Average (lbf):            9,695
Layer No:                          1        2        3        HS
BackCalc. Moduli (ksi):          684       27       15       198
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24        36        48        60
Measured Deflection (mil):      5.21     4.12     3.28      2.57      1.98      1.49
Calc. Deflection (mil):         5.26     3.98     3.26      2.61      2.04      1.56
---------------------------------------------------------------------------------
Station     6.430Righ
Load Average (lbf):            9,801
Layer No:                          1        2        3        HS
BackCalc. Moduli (ksi):        1,110       23       21       200
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24        36        48        60
Measured Deflection (mil):      3.60     3.00     2.43      1.93      1.46      1.03
Calc. Deflection (mil):         3.67     2.86     2.38      1.94      1.54      1.19
```

Figure 6.16 Output results for running the program via *BackGenetic3D* using an FWD file on April 4, 2012 for a flexible pavement.

6.6 TUTORIAL

Based on the theoretical work presented in the previous sections, a software product was developed and a user-friendly GUI has been designed by incorporating the core code in C and C++. The program is called *BackGenetic3D* which presents the backcalculation method using the forward program *MultiSmart3D* and the improved GA. The tutorial for this program is described below.

BackGenetic3D program consists of different types of files including *.exe*, *.ilk*, *.lib*, *.dll*, and manifests for Microsoft Visual C++. The *.lib* file format contains the calculation procedures in C language which are connected to the main code of the program via dynamic-link library (dll). The program can be executed by double clicking on the *.exe* file.

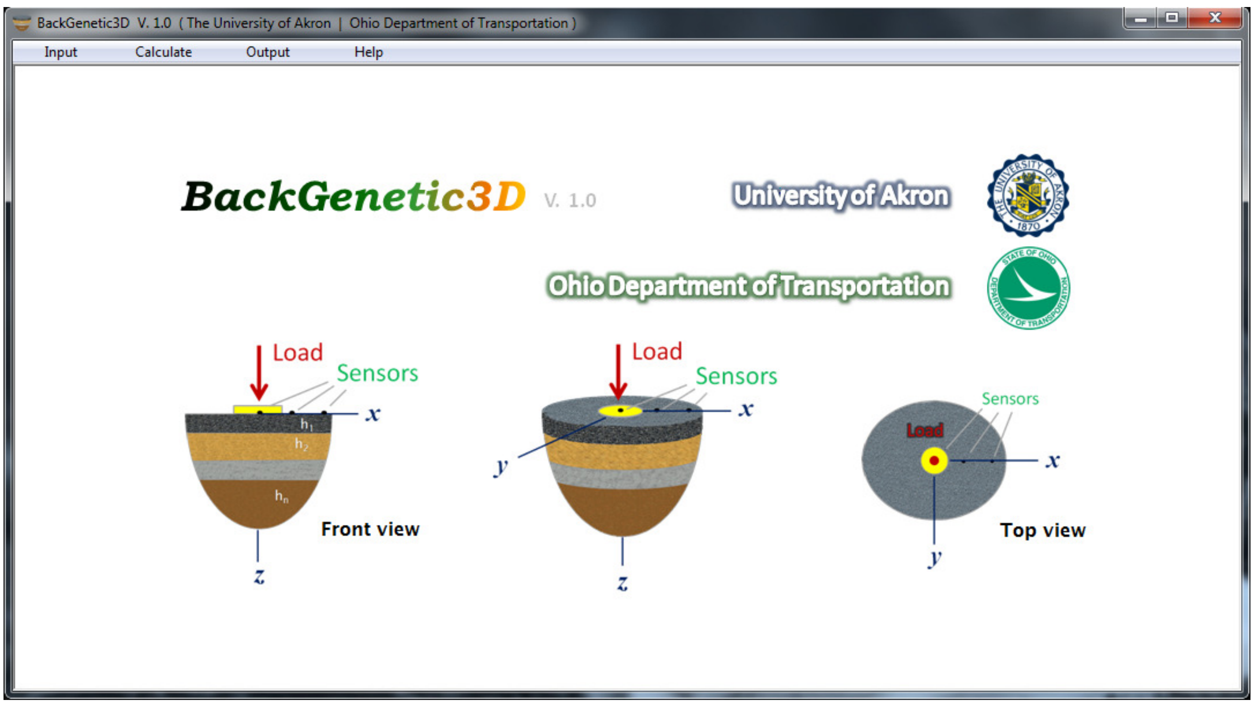


Figure 6.17 The main window of the GUI in *BackGenetic3D*.

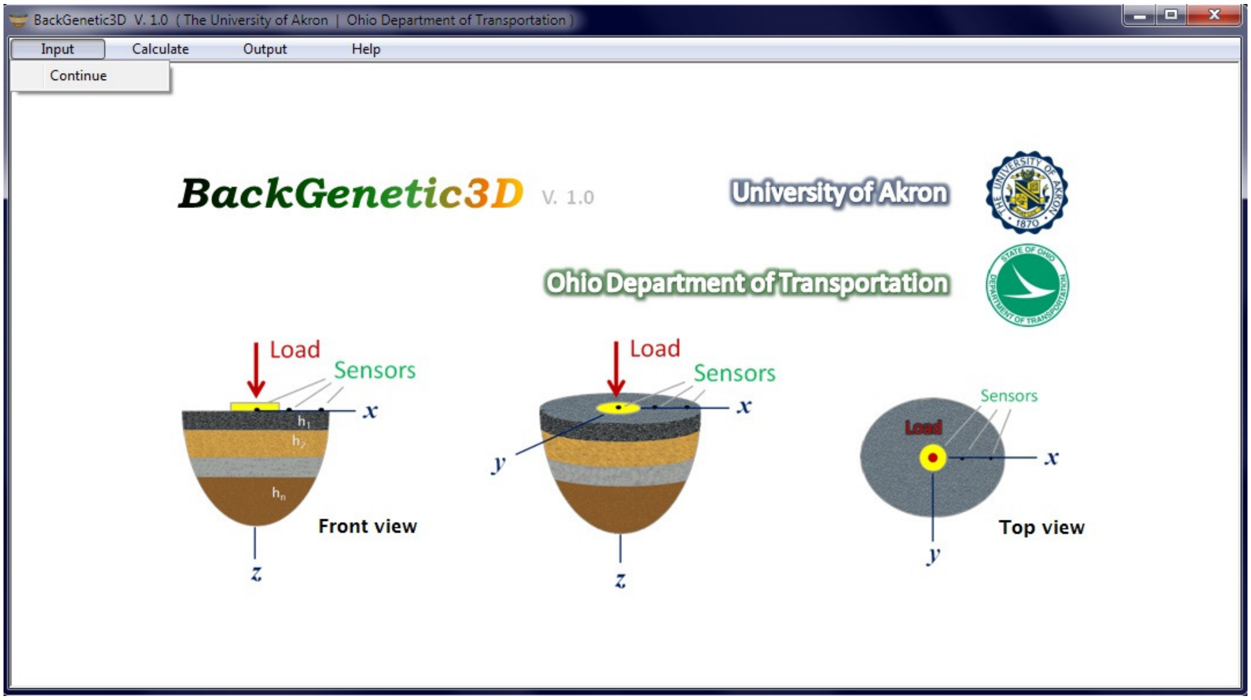


Figure 6.18 “Input” tab in *BackGenetic3D*.

Figure 6.17 shows the main window of the *BackGenetic3D* program. There are four tabs at the menu bar on the top of the window. The first one is **Input** where input information for the calculation can be set. If the **Input** tab is clicked, a drop-down listbox will be displayed (Fig. 6.18). By clicking the **Continue** button, a new window titled **General Information** will appear (Fig. 6.19).

In **General Information** dialog, different conditions can be set for the program including unit selection, case selection, and the type of boundary conditions. There are two separate sections in this window: **Initial Information** and **Thermo Information** (this option is not available now). In the **Initial Information** section the type of the units are to be set. The US system of units is considered as default here to make it easy for use by ODOT engineers. Two options are presented here for the **case** of calculation: **Pure elastic** and **Thermo elastic** (this option is not available now). The **boundary condition** can also be set to **Rigid foundation** or **Half space**. The first version of the *BackGenetic3D* program does not consider the SI units, rigid foundation, and the thermo elastic boundary condition, which will be available in the future versions of the software.

After setting the general information in the first dialog of the GUI, we can continue by clicking the next button and a new window will appear (Fig. 6.20). This window is called **Initial Information** dialog and all data about pavement layers and loads can be defined here. There are two ways to introduce this information to the program. The data can be read from an FWD file or they can be imported manually.

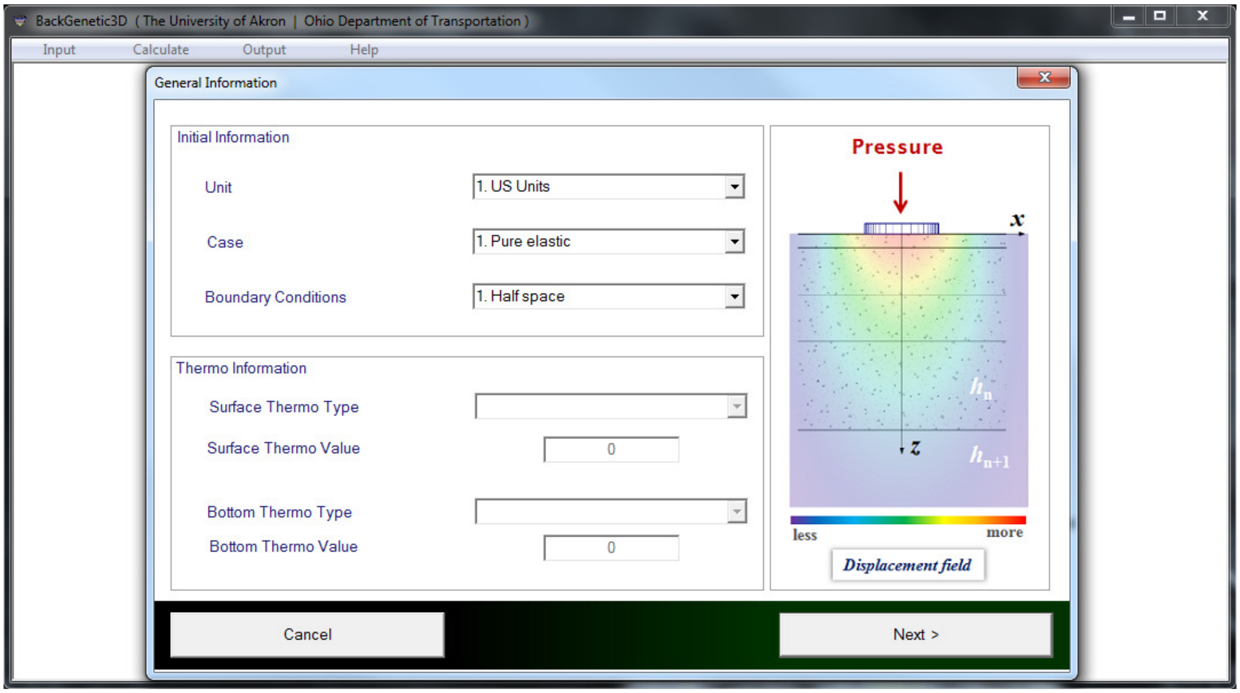


Figure 6.19 General information in *BackGenetic3D*.

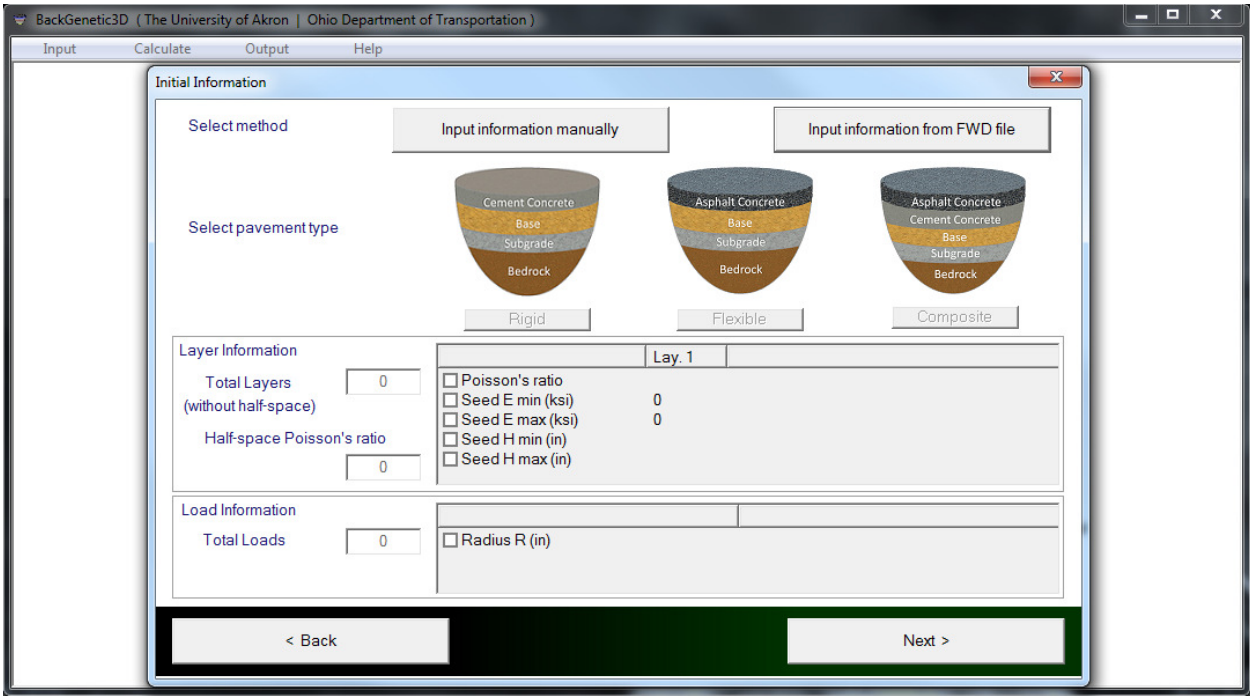


Figure 6.20 Initial information in *BackGenetic3D*.

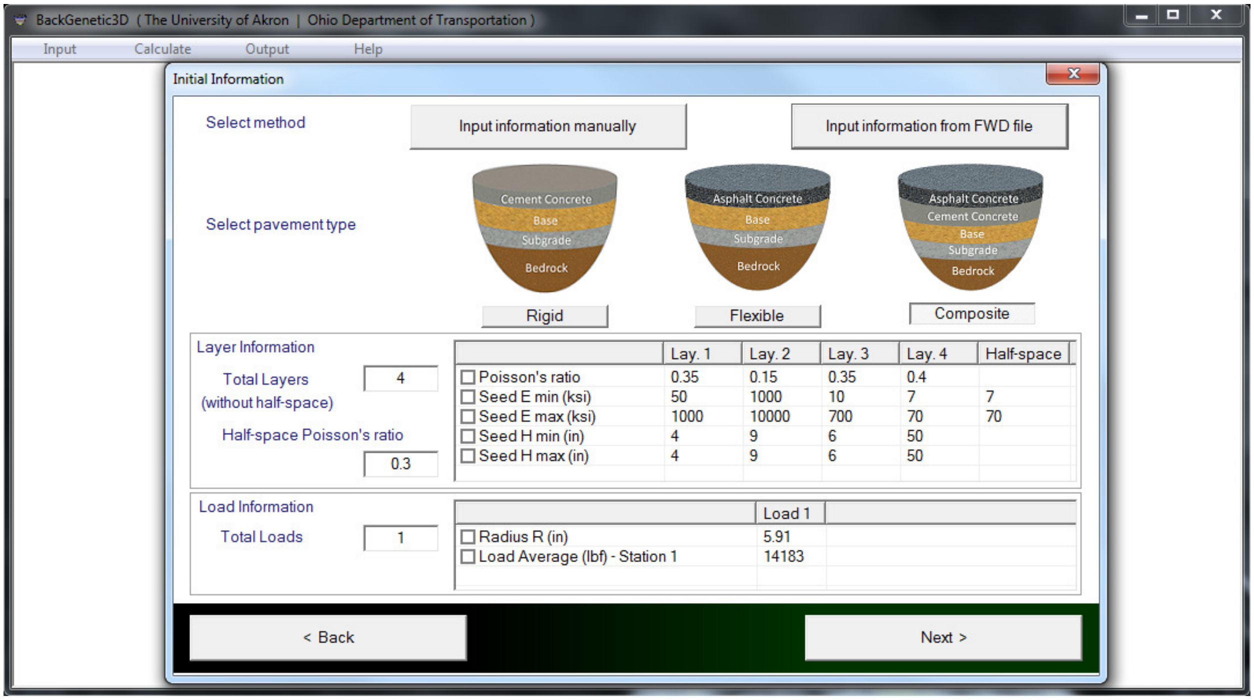


Figure 6.21 Imported information in *BackGenetic3D*.

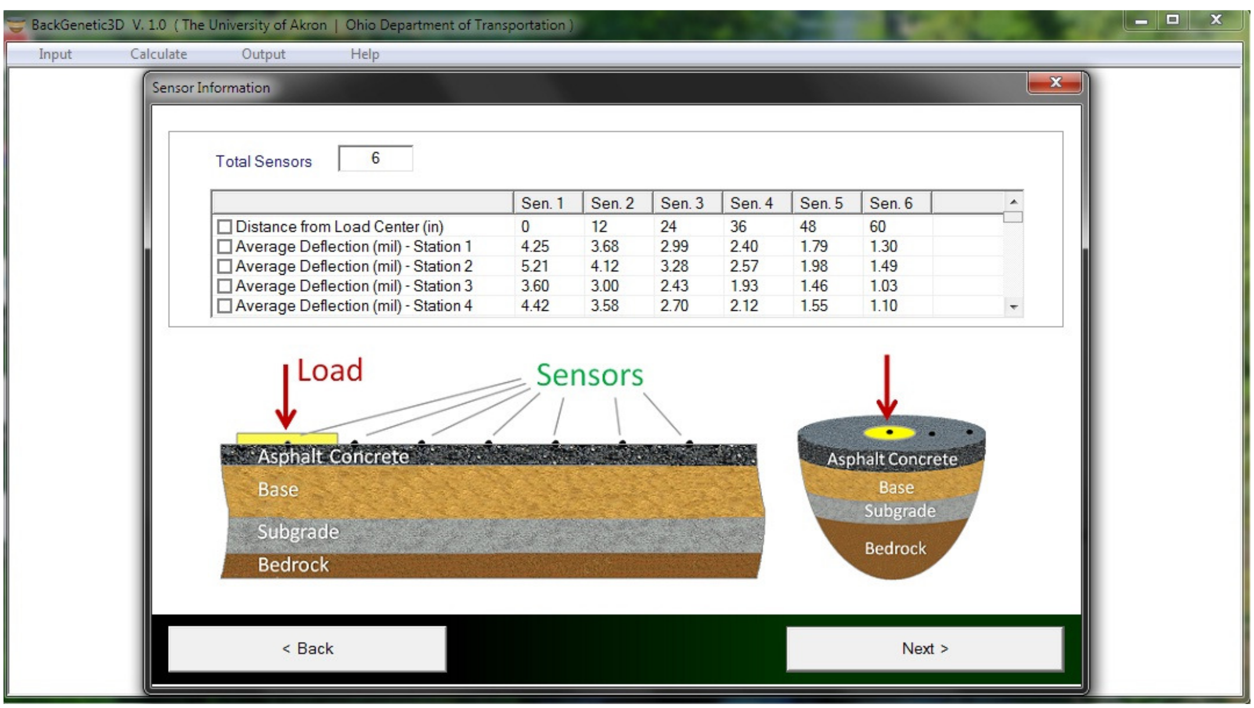


Figure 6.22 Sensor information in *BackGenetic3D*.

If the data are imported from an FWD file, the user needs to choose the type of pavement or layered system. There are three cases available: **Rigid**, **Flexible** and **Composite**. While the type of pavement is selected, all data for layers and loads will be imported into the **Layer Information** and **Load Information** sections. The seed values of the modulus of elasticity and thickness as well as the Poisson's ratios are preset in the program based on the type of pavement but can be changed manually by the user. Figure 6.21 shows the **Initial Information** dialog after importing the data from an FWD file. If the user decides to import the information manually, all these data can be entered in the designed listbox in this dialog. The next dialog which will appear by clicking the **next** button is called **Sensor Information**. In this window the information about the number of sensors and their locations will be shown and the user can set them manually as well. This window is shown in Fig. 6.22.

The last window is the **Objective Function** dialog (Fig. 6.23) which is designed to set the type of objective functions in the backcalculation method. There are two options in this dialog: the first one is the **AVCF** objective function which works perfectly even in the presence of errors. The other one is the **RMS** objective function which works fast in the absence of errors. After hitting the **Finish** button, the main window of the *BackGenetic3D* program will appear again. The program can be executed by clicking on the **RUN** in the **Calculate** tab of the menu bar (Fig. 6.24). The program starts to backcalculate the elastic modulus and thickness as well as the deflections. A new window will pop up which states the end of the calculation procedure (Fig. 6.25). The user can access the results by clicking on the **Output** tab in the menu bar (Fig. 6.26). A sample of an FWD file and the corresponding input and output files are shown in Figs. 6.27-29.

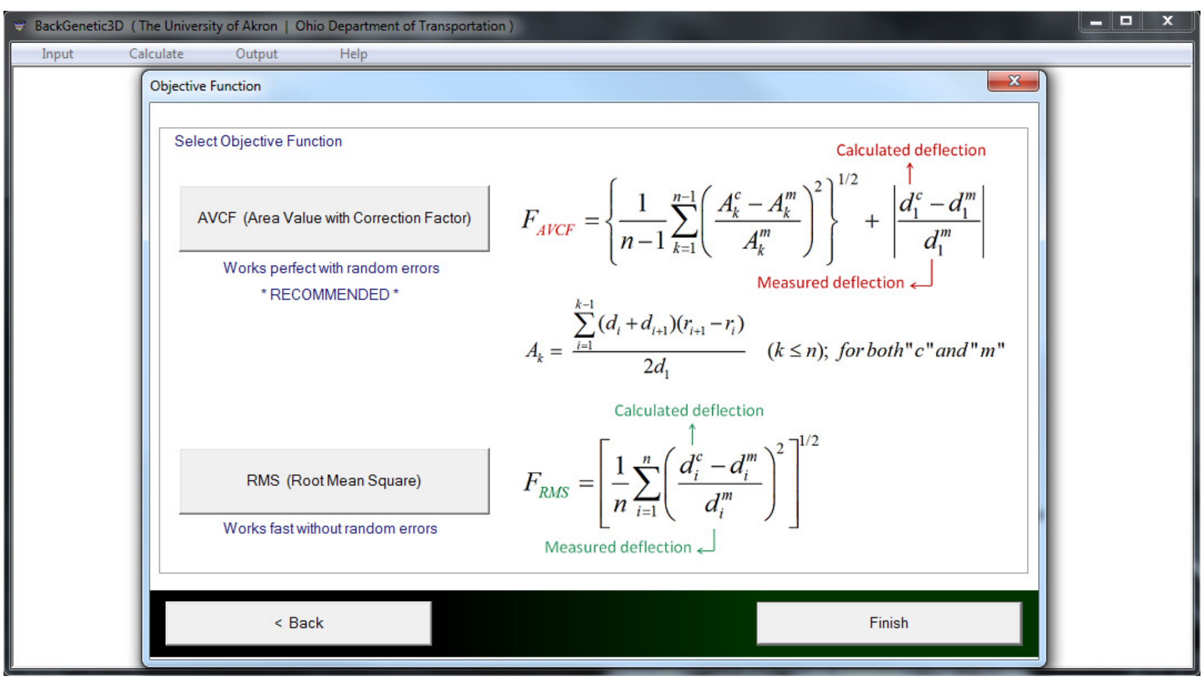


Figure 6.23 Objective function in *BackGenetic3D*.

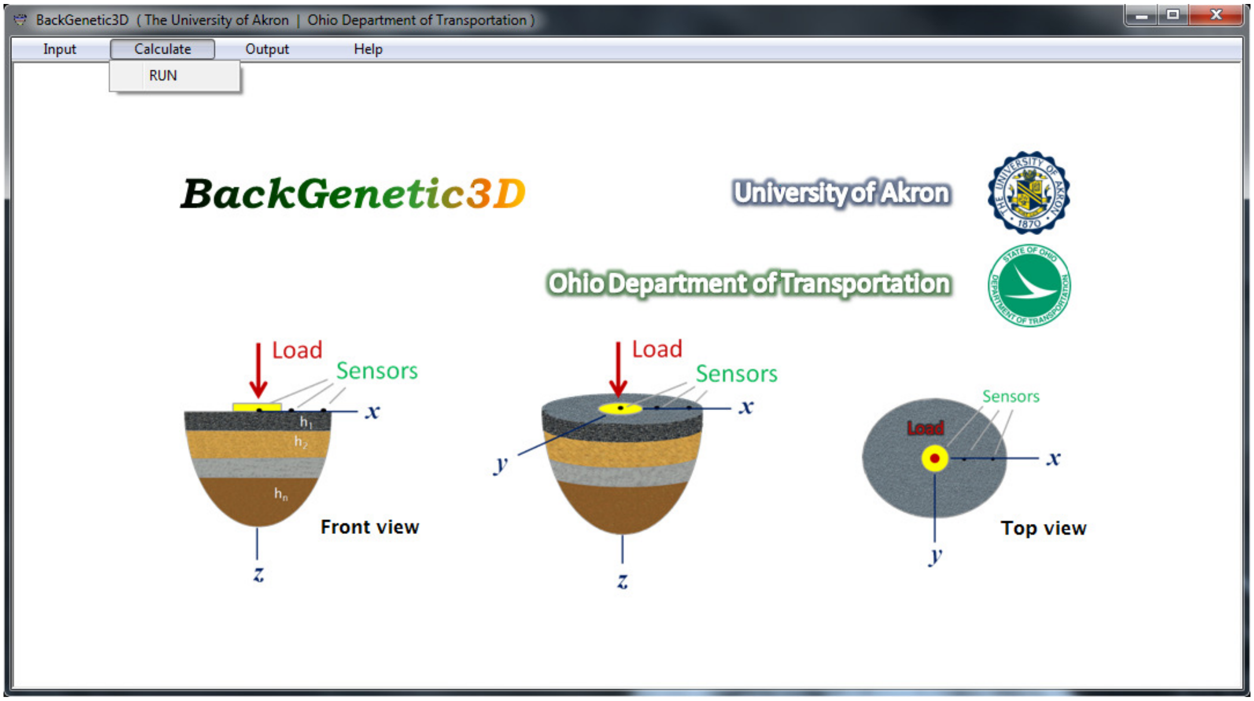


Figure 6.24 Calculate tab in *BackGenetic3D.*

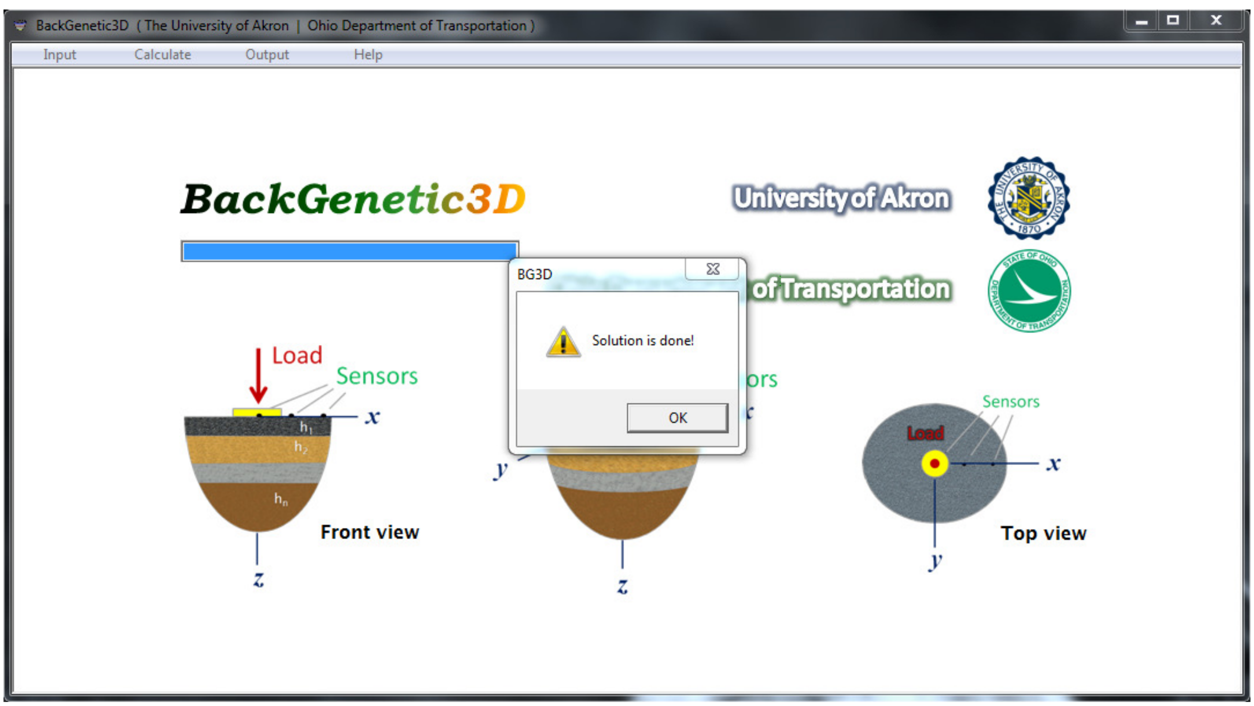


Figure 6.25 End of calculations in *BackGenetic3D*.

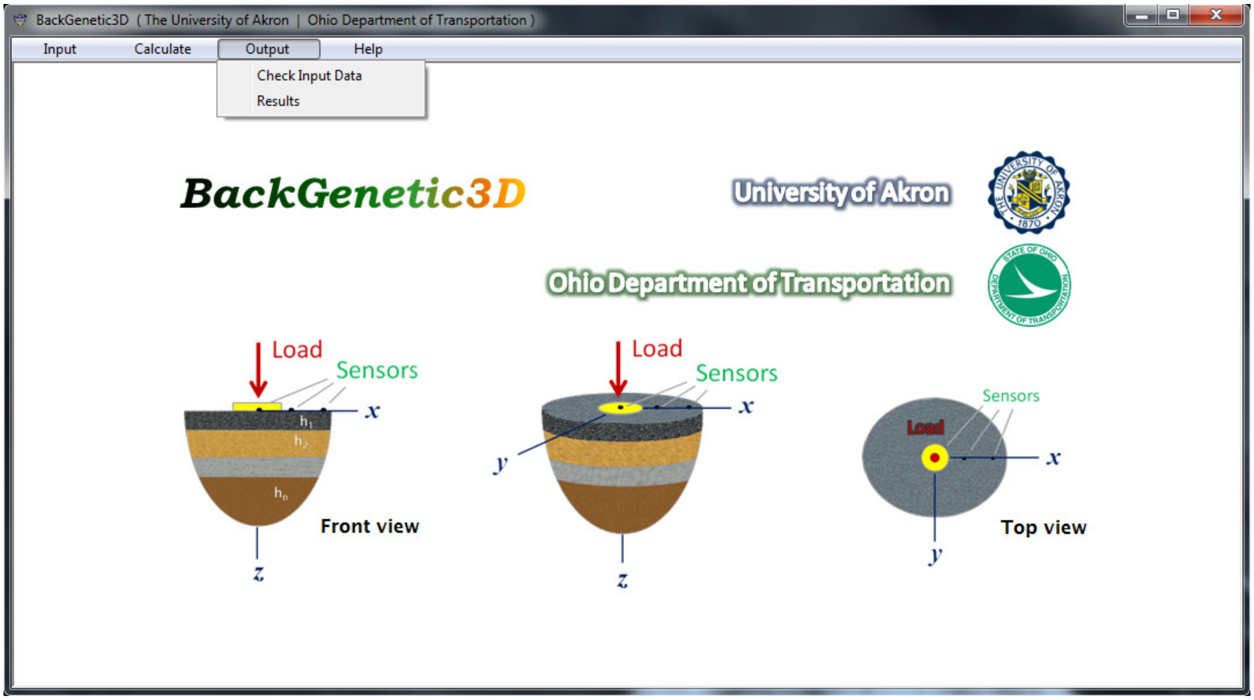
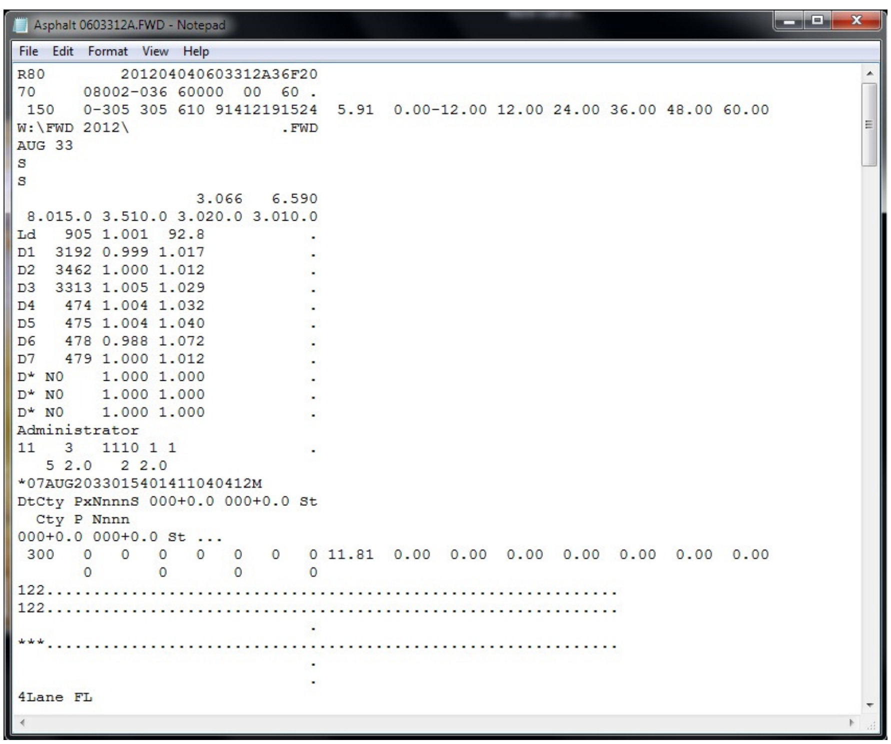
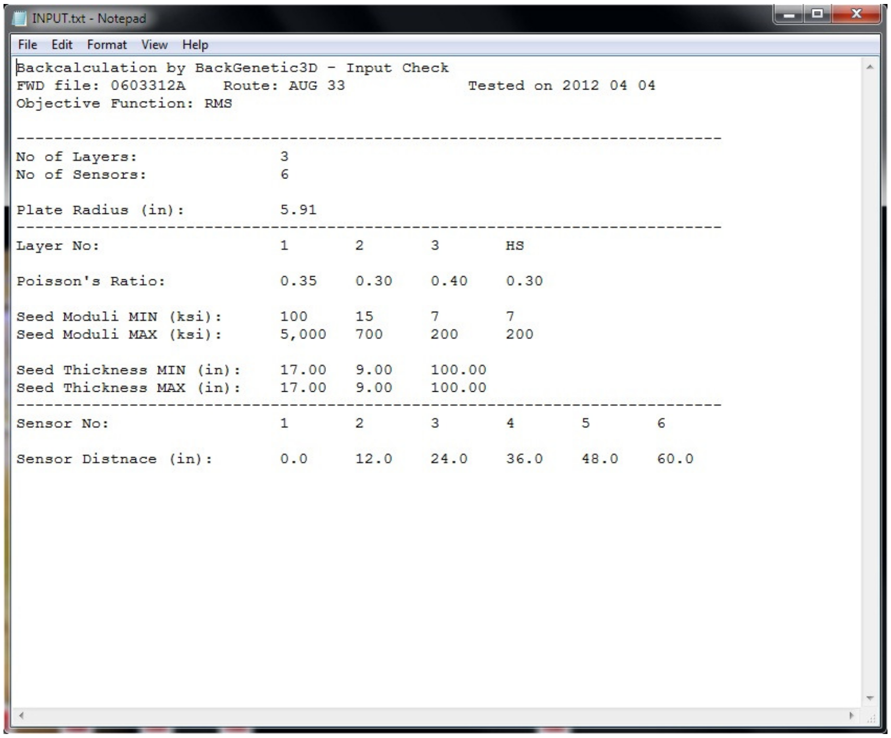


Figure 6.26 Output tab in *BackGenetic3D*.



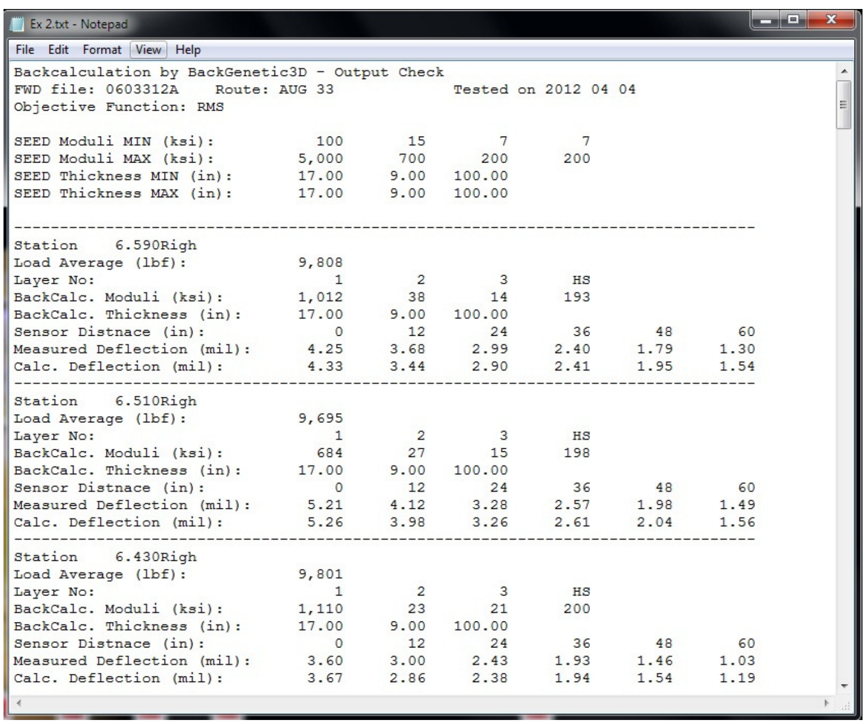

```
R80         201204040603312A36F20
70      08002-036 60000  00  60 .
 150    0-305 305 610 91412191524  5.91  0.00-12.00 12.00 24.00 36.00 48.00 60.00
W:\FWD 2012\                   .FWD
AUG 33
S
S
                  3.066   6.590
 8.015.0 3.510.0 3.020.0 3.010.0
Ld   905 1.001  92.8           .
D1  3192 0.999 1.017           .
D2  3462 1.000 1.012           .
D3  3313 1.005 1.029           .
D4   474 1.004 1.032           .
D5   475 1.004 1.040           .
D6   478 0.988 1.072           .
D7   479 1.000 1.012           .
D* NO    1.000 1.000           .
D* NO    1.000 1.000           .
D* NO    1.000 1.000           .
Administrator
11   3   1110 1 1              .
   5 2.0   2 2.0
*07AUG2033015401411040412M
DtCty PxNnnnS 000+0.0 000+0.0 St
  Cty P Nnnn
000+0.0 000+0.0 St ...
 300    0    0    0    0    0    0    0 11.81  0.00  0.00  0.00  0.00  0.00  0.00  0.00
        0         0         0         0
122............................................................
122............................................................
                               .
***............................................................
                               .
                               .
4Lane FL
```

Figure 6.27 An FWD file as an input file for *BackGenetic3D*.



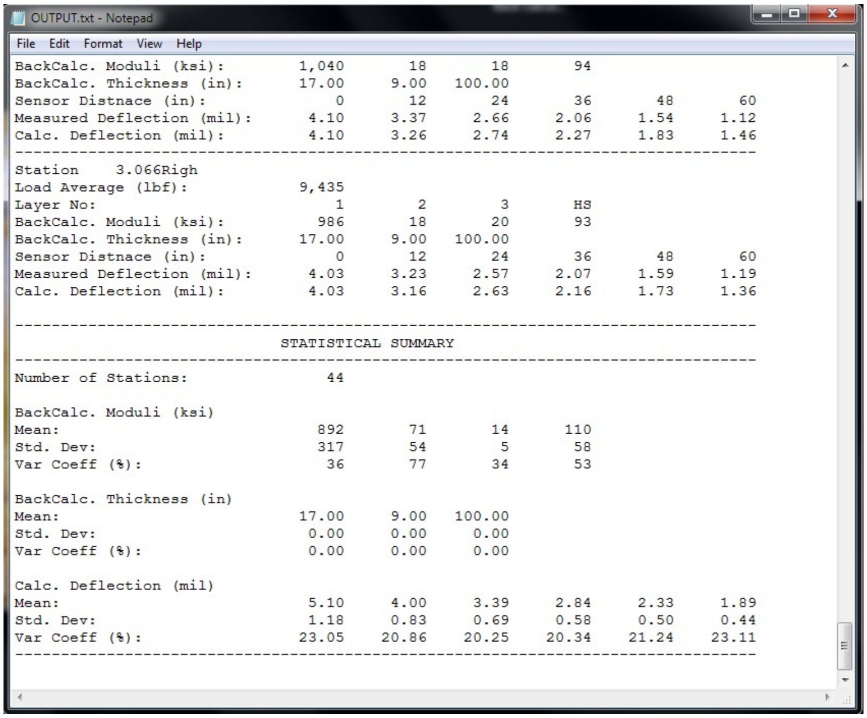
```
Backcalculation by BackGenetic3D - Input Check
FWD file: 0603312A    Route: AUG 33            Tested on 2012 04 04
Objective Function: RMS

---------------------------------------------------------------------------
No of Layers:               3
No of Sensors:              6

Plate Radius (in):          5.91
---------------------------------------------------------------------------
Layer No:                   1       2       3       HS

Poisson's Ratio:            0.35    0.30    0.40    0.30

Seed Moduli MIN (ksi):      100     15      7       7
Seed Moduli MAX (ksi):      5,000   700     200     200

Seed Thickness MIN (in):    17.00   9.00    100.00
Seed Thickness MAX (in):    17.00   9.00    100.00
---------------------------------------------------------------------------
Sensor No:                  1       2       3       4       5       6

Sensor Distnace (in):       0.0     12.0    24.0    36.0    48.0    60.0
```

Figure 6.28 *Input Check* file in *BackGenetic3D.*



```
Backcalculation by BackGenetic3D - Output Check
FWD file: 0603312A    Route: AUG 33            Tested on 2012 04 04
Objective Function: RMS

SEED Moduli MIN (ksi):           100       15        7        7
SEED Moduli MAX (ksi):         5,000      700      200      200
SEED Thickness MIN (in):       17.00     9.00   100.00
SEED Thickness MAX (in):       17.00     9.00   100.00

------------------------------------------------------------------------------
Station     6.590Righ
Load Average (lbf):            9,808
Layer No:                          1        2        3       HS
BackCalc. Moduli (ksi):        1,012       38       14      193
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24       36       48       60
Measured Deflection (mil):      4.25     3.68     2.99     2.40     1.79     1.30
Calc. Deflection (mil):         4.33     3.44     2.90     2.41     1.95     1.54
------------------------------------------------------------------------------
Station     6.510Righ
Load Average (lbf):            9,695
Layer No:                          1        2        3       HS
BackCalc. Moduli (ksi):          684       27       15      198
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24       36       48       60
Measured Deflection (mil):      5.21     4.12     3.28     2.57     1.98     1.49
Calc. Deflection (mil):         5.26     3.98     3.26     2.61     2.04     1.56
------------------------------------------------------------------------------
Station     6.430Righ
Load Average (lbf):            9,801
Layer No:                          1        2        3       HS
BackCalc. Moduli (ksi):        1,110       23       21      200
BackCalc. Thickness (in):      17.00     9.00   100.00
Sensor Distnace (in):              0       12       24       36       48       60
Measured Deflection (mil):      3.60     3.00     2.43     1.93     1.46     1.03
Calc. Deflection (mil):         3.67     2.86     2.38     1.94     1.54     1.19
```

Figure 6.29 *Output Results* file in *BackGenetic3D.*



```
BackCalc. Moduli (ksi):          1,040       18       18       94
BackCalc. Thickness (in):        17.00     9.00   100.00
Sensor Distnace (in):                0       12       24       36       48       60
Measured Deflection (mil):        4.10     3.37     2.66     2.06     1.54     1.12
Calc. Deflection (mil):           4.10     3.26     2.74     2.27     1.83     1.46
--------------------------------------------------------------------------------
Station    3.066Righ
Load Average (lbf):              9,435
Layer No:                            1        2        3       HS
BackCalc. Moduli (ksi):            986       18       20       93
BackCalc. Thickness (in):        17.00     9.00   100.00
Sensor Distnace (in):                0       12       24       36       48       60
Measured Deflection (mil):        4.03     3.23     2.57     2.07     1.59     1.19
Calc. Deflection (mil):           4.03     3.16     2.63     2.16     1.73     1.36

--------------------------------------------------------------------------------
                            STATISTICAL SUMMARY
--------------------------------------------------------------------------------
Number of Stations:                 44

BackCalc. Moduli (ksi)
Mean:                              892       71       14      110
Std. Dev:                          317       54        5       58
Var Coeff (%):                      36       77       34       53

BackCalc. Thickness (in)
Mean:                            17.00     9.00   100.00
Std. Dev:                         0.00     0.00     0.00
Var Coeff (%):                    0.00     0.00     0.00

Calc. Deflection (mil)
Mean:                             5.10     4.00     3.39     2.84     2.33     1.89
Std. Dev:                         1.18     0.83     0.69     0.58     0.50     0.44
Var Coeff (%):                   23.05    20.86    20.25    20.34    21.24    23.11
--------------------------------------------------------------------------------
```

Figure 6.30 Statistical summary of the backcalculated results via *BackGenetic3D* for an FWD file on April 4, 2012 for a flexible pavement.

6.7 STATISTICAL SUMMARY OF THE OUTPUT RESULTS

Figure 6.30 shows the statistical summary of the backcalculated results using *BackGenetic3D* for an FWD file that was recorded on April 4, 2012 for a flexible pavement. The statistics are presented for the backcalculated elastic modulus and backcalculated thickness for each layer, as well as the calculated deflections at each sensor. The mean value together with standard deviation and the coefficients of variation are considered for statistical analysis based on the total number of stations that is considered in *BackGenetic3D* program.

CHAPTER 7 MODEL VALIDATION and FIELD EVALUATION

7.0 INTRODUCTION

In this chapter, several examples are presented to demonstrate the capability of the *BackGenetic3D* program. One-layer pavement was analyzed by the program manually to understand the effects of the measurement errors on backcalculated results. The program is also applied to three-layer and twenty-three-layer structures. In the three-layer case, the moduli and thickness data imported from an FWD file of a composite-type pavement are used as seeds.

7.1 ONE-LAYER PAVEMENT STRUCTURE

In this section, we assume a one-layer pavement structure over a halfspace. The schematic view and the material and geometrical properties are presented in Fig. 7.1. We assume that seven sensors (i = 1 to 7, starting from the center of the loading, Stubstad *et al* 2000) are used in the FWD system with deflections listed in Table 7.1. To determine the effect of the measurement errors on backcalculated layer elastic modulus and thickness, a group of 40 simulated measurement deflection errors is generated. After obtaining the simulated measurement data with errors, two objective functions are used to backcalculate the modulus and thickness of the pavement. The backcalculation error due to the measurement error can be obtained by comparing the backcalculated modulus and thickness to the measured values.

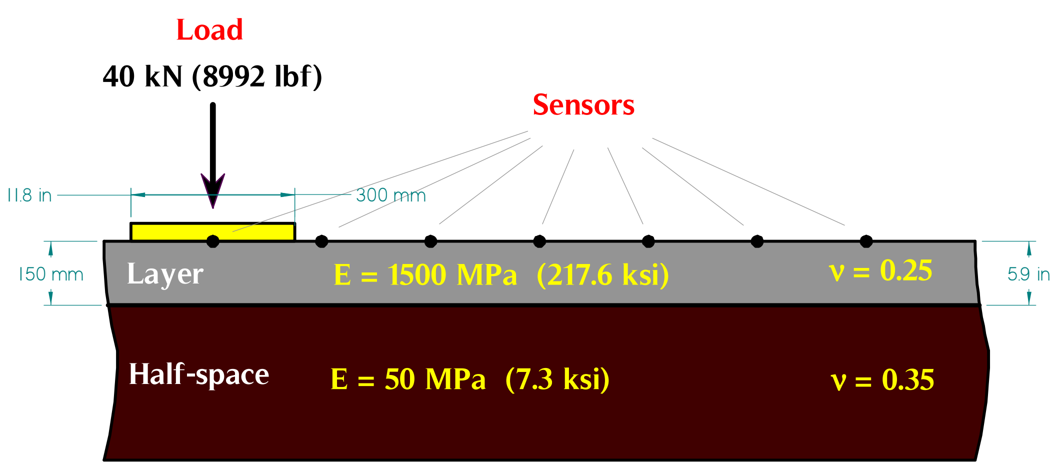


Figure 7.1 Schematic view of one-layer pavement structure over a halfspace.

Table 7.1 Forward calculated deflections of one-layer pavement over a halfspace

Distance from load center		Deflections	
mm	in	µm	mil
0.0	0.0	982.2	38.7
203.2	8.0	791.9	31.2
304.8	12.0	669.9	26.4
457.2	18.0	516.4	20.3
609.6	24.0	400.6	15.8
914.4	36.0	257.3	10.1
1524.0	60.0	143.4	5.6

Figures 7.2 and 7.3 illustrate the backcalculated results for the elastic moduli and thickness of one-layer pavement structure over a halfspace using the objective functions RMS and AVCF. Elastic moduli and thickness are backcalculated using the improved GA developed by The University of Akron group. When there is no systematic and random error in the measurement data (Figs. 7.2 and 7.3 (a)), the backcalculated values of the thickness of top layer and the elastic moduli of the top layer and halfspace are exactly equal to the measured values. As can be observed from Figs. 7.2 and 7.3 (a), when there is no error, both objective functions work perfectly well in backcalculation of elastic moduli and thickness with only very small standard deviation.

Now we assume that there are random errors in measurement deflections while no systematic error exists. The backcalculated results for moduli and thickness are presented in Figs. 7.2 and 7.3 (b) for this case. Despite insignificant standard deviation for the halfspace, it is obvious that the standard deviation for elastic modulus and thickness of the top layer are smaller when we use AVCF as the objective function in comparison to the RMS function. Also at the top layer, the backcalculated modulus by AVCF function is closer to the exact value than that by RMS function, which shows that AVCF is more accurate and reliable in backcalculation analysis. While both objective functions can backcalculate accurately the modulus in the subgrade layer, the AVCF function is significantly more accurate than RMS in backcalculation of thickness in top pavement layer.

Figures 7.2 and 7.3 (c) shows the backcalculated results for elastic moduli and thickness of one-layer pavement structure over a halfspace using the objective functions RMS and AVCF when there is only systematic error. The backcalculated elastic moduli and thickness are very close to the exact value in this case. While the standard deviation for the backcalculation of the elastic modulus is acceptable using the RMS function, the standard deviation using the AVCF function is completely negligible.

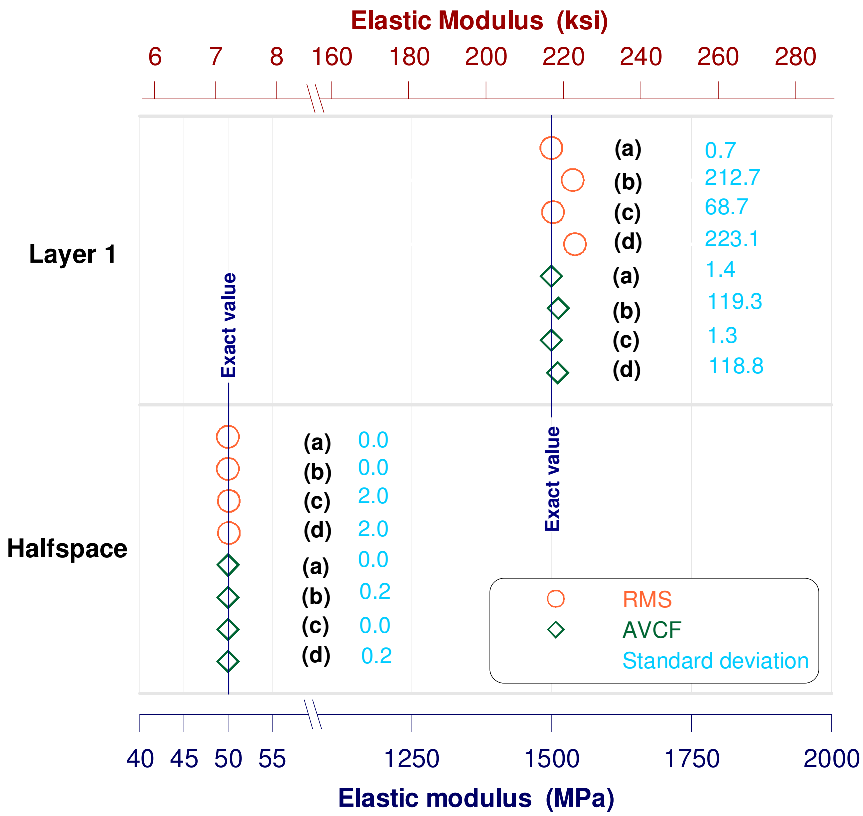


Figure 7.2 Backcalculated Young's moduli E_1 and E_2 by two objective functions where (a) no error exists, (b) only random error exists, (c) only systematic error exists, and (d) both random and systematic errors exist.

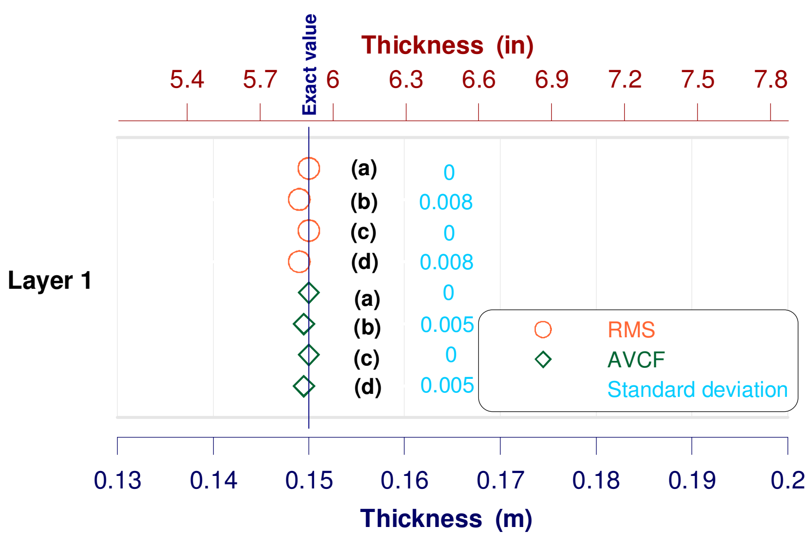


Figure 7.3 Backcalculated thickness h_1 by two objective functions where (a) no error exists, (b) only random error exists, (c) only systematic error exists, and (d) both random and systematic errors exist.

We now consider the situation where not only the systematic errors but also the random errors exist. As shown in Figs. 7.2 and 7.3 (d), under the influence of the combined errors, the backcalculated results using the RMS function is clearly not satisfactory except for the elastic modulus of the second pavement layer. However, accurate results can still be obtained using the AVCF objective function. The results for the backcalculated thickness of the top layer in this case confirm also the superiority of the AVCF over RMS.

7.2 THREE-LAYER PAVEMENT STRUCTURE

A three-layer pavement structure over a halfspace is also considered for the backcalculation of elastic modulus and thickness as shown in Fig. 7.4. The deflections which are calculated using our *MultiSmart3D* program for seven sensors are illustrated in Table 7.2. Backcalculated elastic modulus and thickness are presented in Figs. 7.5 and 7.6. The backcalculated deflections using the *BackGenetic3D* program is identical to the calculated deflections by *MultiSmart3D* with one-digit precision. The range of elastic moduli is considered based on the recommended seed values for composite pavement containing asphalt concrete, concrete, granular base, and subgrade layer system. To backcalculate the elastic moduli of different layers, the thickness of each pavement layer is considered to be exact, whilst for backcalculation of thickness, the elastic moduli are fixed. The backcalculated results for moduli are acceptable for all layers using both objective functions. The backcalculated thicknesses are almost acceptable except for the third layer. It is noteworthy that the subgrade material properties and seed values could significantly affect the backcalculated results (ASTM 2003).

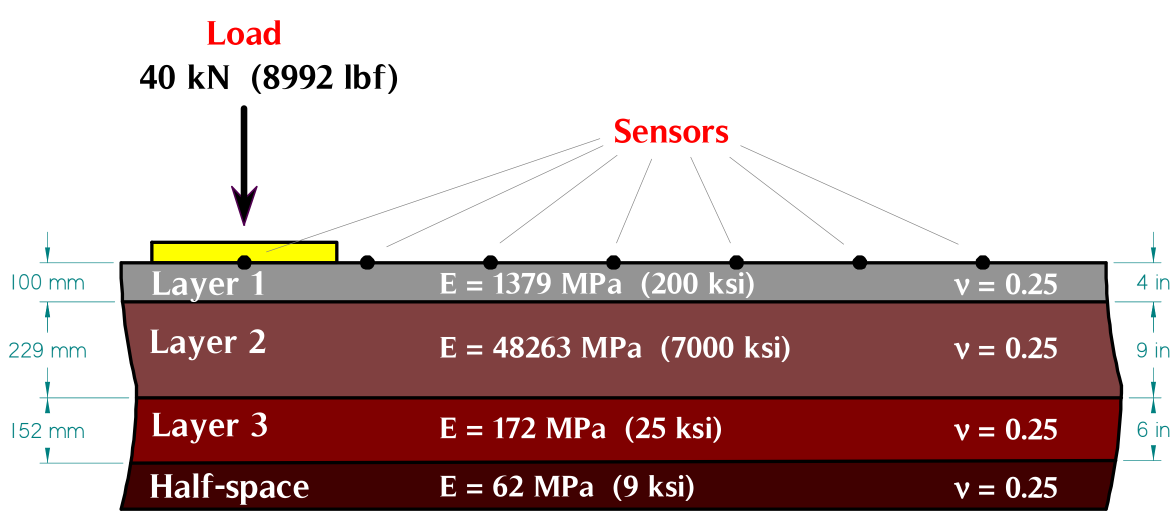


Figure 7.4 Schematic view of a three-layer pavement structure over a halfspace.

Table 7.2 Forward calculated deflections of a three-layer pavement over a halfspace

Distance from load center		Deflections	
mm	in	μm	mil
0.0	0.0	229.6	9.04
203.2	8.0	193.5	7.62
304.8	12.0	189.5	7.46
457.2	18.0	183.6	7.23
609.6	24.0	176.8	6.96
914.4	36.0	161.5	6.36
1524.0	60.0	130.6	5.14

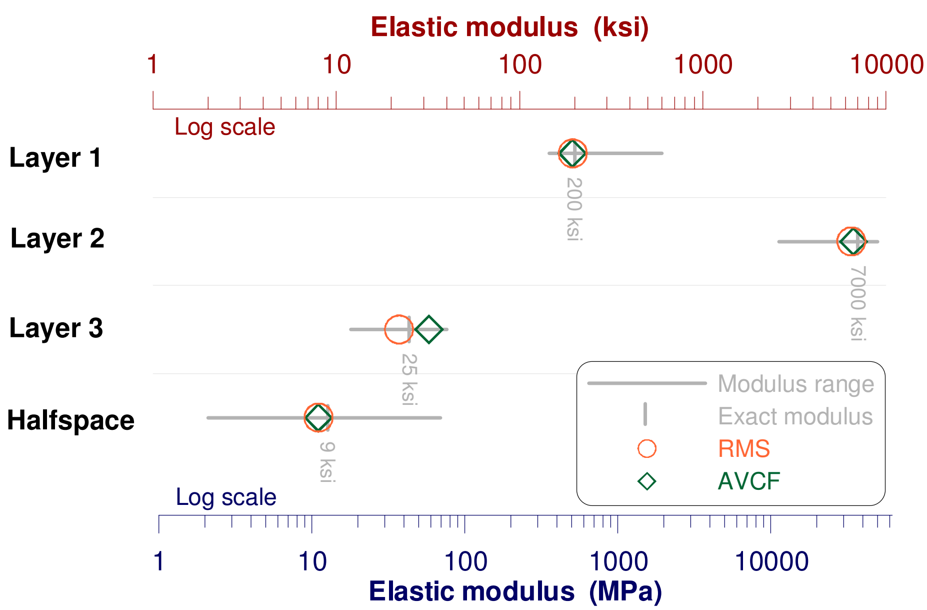


Figure 7.5 Backcalculated Young's moduli E_i by two objective functions for a three-layer pavement structure over a halfspace.

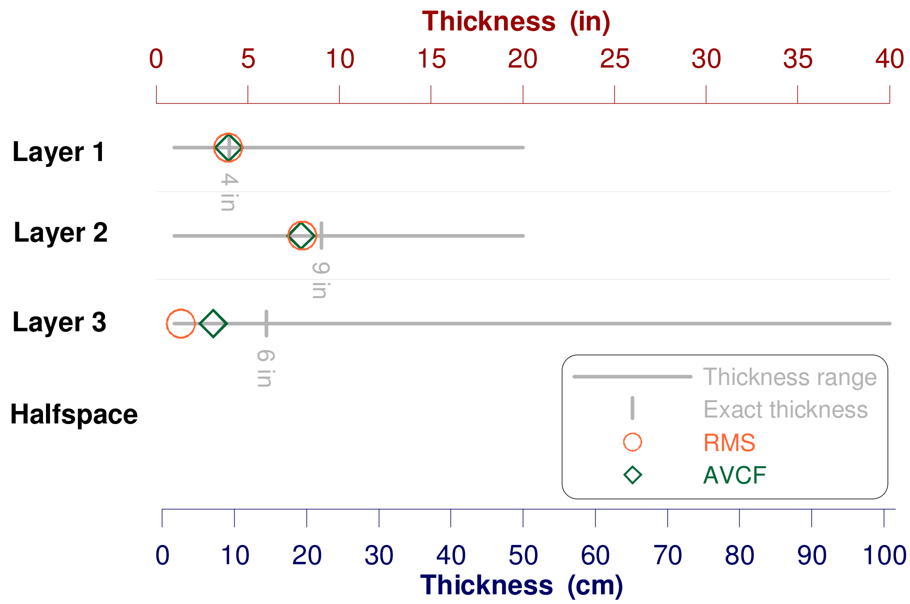


Figure 7.6 Backcalculated thicknesses h_i by two objective functions for a three-layer pavement structure over a halfspace.

7.3 TWENTY-THREE-LAYER PAVEMENT STRUCTURE

We further backcalculate the elastic modulus and thickness of each layer for a twenty-three-layer structure over a halfspace. The initial values for the elastic modulus and thickness of each pavement layer are chosen using the following equations.

$$
\begin{aligned}
&E_{i+1} / E_1 = (i = 1, 2, ..., 23) \\
&0.9, 0.9, 0.9, 0.8, 0.8, 0.8, 0.7, 0.7, 0.7, 0.9, 0.9, 0.9, \\
&0.8, 0.8, 0.8, 0.7, 0.7, 0.7, 0.5, 0.9, 0.9, 0.5, 0.1 \\
&h_{i+1} / h_1 = (i = 1, 2, ..., 22) \\
&0.2, 0.3, 0.5, 0.4, 0.4, 0.4, 0.3, 0.3, 0.4, 0.3, 0.3, 0.4, \\
&0.3, 0.3, 0.4, 0.3, 0.3, 0.4, 0.3, 0.3, 0.4, 0.5
\end{aligned}
\quad \text{Eq. (7.1)}
$$

where the elastic modulus and thickness of the first layer are selected to be 2070 MPa (300 ksi) and 0.254 m (10 in), respectively. The surface deflection of the pavement is calculated using our forward program *MultiSmart3D* at seven sensors as listed in Table 7.3.

The backcalculated deflections using the *BackGenetic3D* program is identical to the calculated deflections by *MultiSmart3D* with two-digit precision. Figures 7.7 and 7.8 illustrate the elastic moduli and thicknesses backcalculated by two objective functions for the twenty-three-layer pavement described in Eq. (7.1). It is clear that the backcalculated elastic moduli and thicknesses for most layers are closer to the exact values using the AVCF as objective function in comparison to the RMS function. The backcalculated moduli and thickness for some layers are not accurate enough due to the insufficient information on the surface. The importance of GA parameters on the backcalculation procedure is undeniable. The selection of optimal GA parameters to be adopted for backcalculation and the use of advanced numerical methods could be potential approaches to increase the accuracy of the backcalculated results in the presence of a structure with numerous layers.

The new backcalculation program presented here can be applied to any number of layers to backcalculate the elastic modulus as well as the thickness while the other programs can only backcalculate the elastic modulus with limited number of pavement layers.

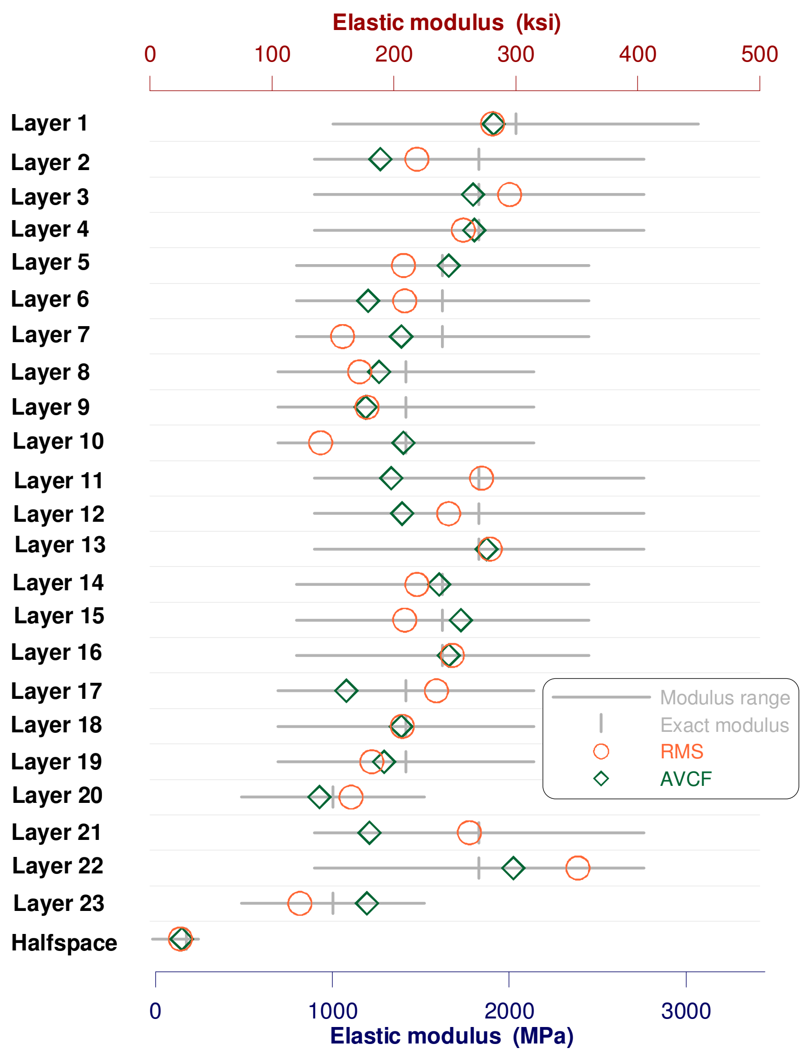


Figure 7.7 Backcalculated Young's moduli E_i by two objective functions for a twenty-three-layer structure over a halfspace.

Table 7.3 Forward calculated deflections of twenty-three-layer pavement over a halfspace

Distance from load center		Deflections	
mm	in	µm	mil
0.0	0.0	106.7	4.20
203.2	8.0	58.9	2.32
304.8	12.0	46.5	1.83
457.2	18.0	38.6	1.52
609.6	24.0	34.5	1.36
914.4	36.0	29.7	1.17
1524.0	60.0	24.9	0.98

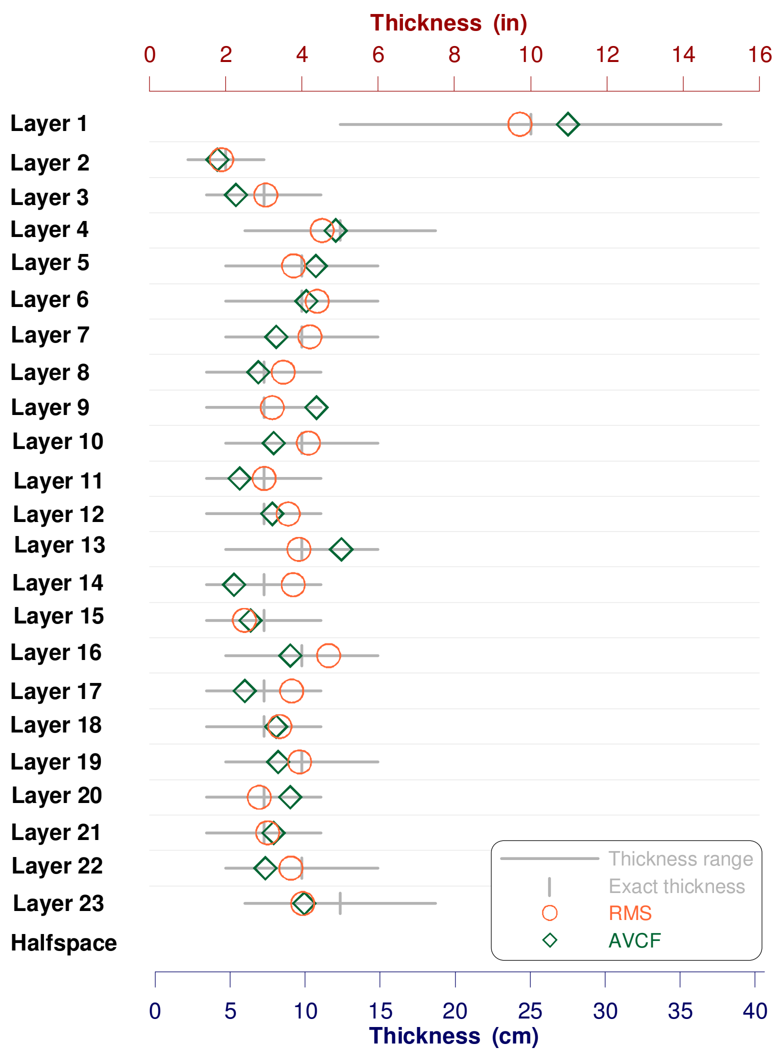
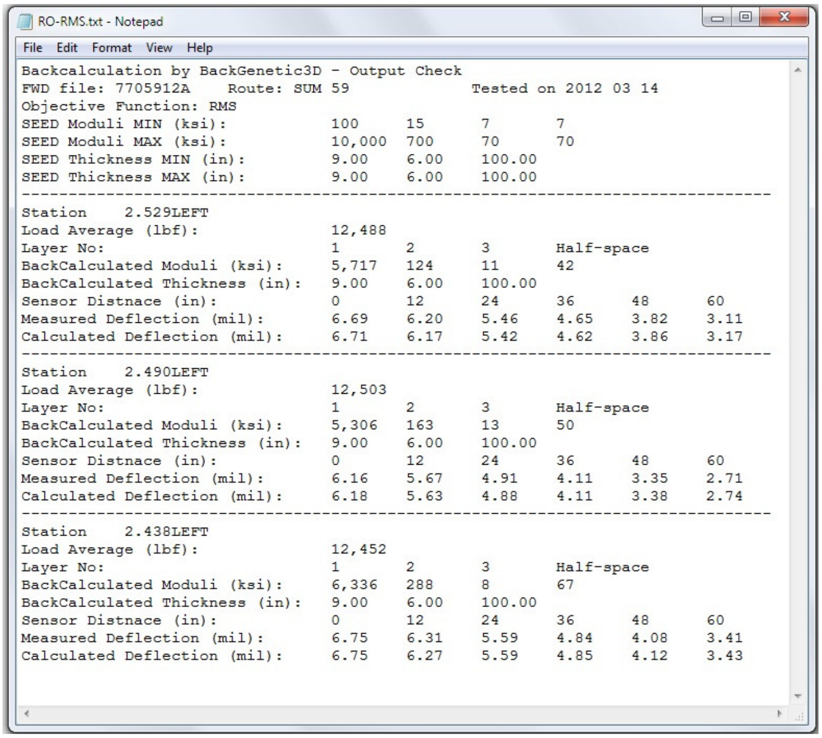


Figure 7.8 Backcalculated thicknesses h_i by two objective functions for a twenty-three-layer structure over a halfspace.

7.4 EXAMPLES USING FWD FILES

In this section, three examples of real pavements are presented in which the backcalculation is performed using the corresponding FWD files via the *BackGenetic3D* program. The data are imported from FWD files which were recorded in-situ on March 14 2012, March 27 2012, and April 4 2012 on rigid, composite, and flexible pavements, respectively. We use the RMS and AVCF as objective functions in the calculation. The output results for the first three stations are illustrated in Figs. 7.9-14. The results of backcalculated moduli for each station are within the range of determined seed values. Different backcalculated moduli are obtained for different stations since the recorded sensor deflections are dissimilar. Although the thickness of each layer is assumed to be fixed in these examples, it is not necessary to be fixed and the program can backcalculate the thickness providing that the range of seed values are set for each layer. Statistical analysis on the backcalculated moduli and thicknesses based on the total number of stations can be of great importance to validate the backcalculated results with real pavements.

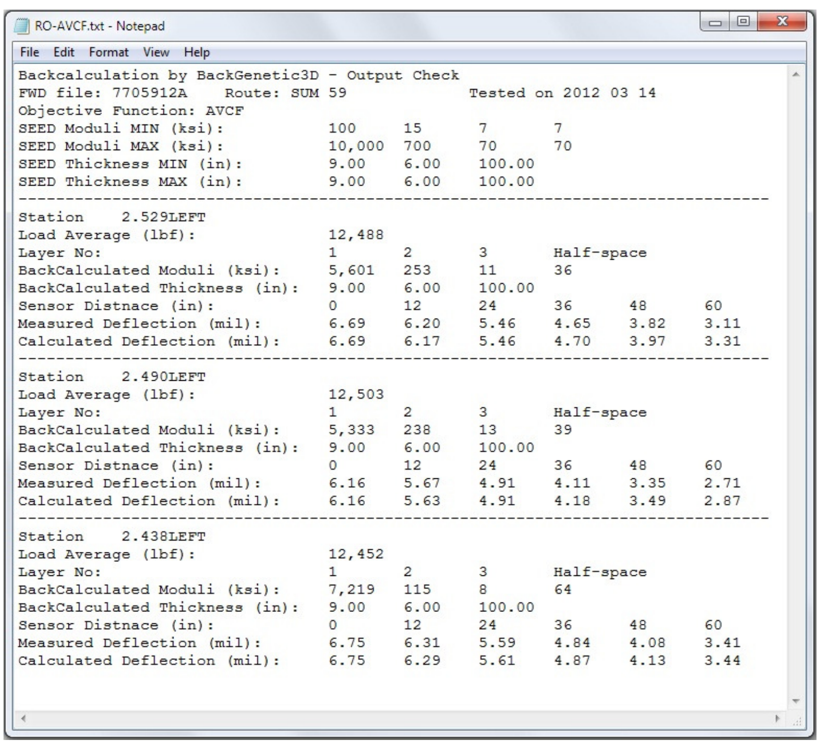
The processing time of backcalculation depends not only on the type of pavement structure and the number of stations in the FWD file but also on the time that convergence happens. Table 7.4 shows the processing time for six pavements (two rigid, two flexible, and two composite pavements) before and after the optimization of the genetic parameter and statistical calculations. The average running time of typical FWD files with rigid, flexible, and composite pavement is 6.3, 13.7, 40.2, 38.2, 18.1, and 18.2 seconds, respectively. Since the number of genes in GA is fixed in the *BackGenetic3D* program, the maximum value of processing time for any type of pavement is going to be about 40 seconds for each station. As one can observe clearly that the backcalculated moduli are very close in all cases. However, the total processing time for each pavement is decreased significantly 44%, 57%, 81%, 66%, 52%, and 58%, respectively.



RO-RMS.txt - Notepad

```
Backcalculation by BackGenetic3D - Output Check
FWD file: 7705912A    Route: SUM 59            Tested on 2012 03 14
Objective Function: RMS
SEED Moduli MIN (ksi):           100     15      7       7
SEED Moduli MAX (ksi):           10,000  700     70      70
SEED Thickness MIN (in):         9.00    6.00    100.00
SEED Thickness MAX (in):         9.00    6.00    100.00
--------------------------------------------------------------------------------
Station    2.529LEFT
Load Average (lbf):              12,488
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     5,717   124     11      42
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.69    6.20    5.46    4.65    3.82    3.11
Calculated Deflection (mil):     6.71    6.17    5.42    4.62    3.86    3.17
--------------------------------------------------------------------------------
Station    2.490LEFT
Load Average (lbf):              12,503
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     5,306   163     13      50
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.16    5.67    4.91    4.11    3.35    2.71
Calculated Deflection (mil):     6.18    5.63    4.88    4.11    3.38    2.74
--------------------------------------------------------------------------------
Station    2.438LEFT
Load Average (lbf):              12,452
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     6,336   288     8       67
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.75    6.31    5.59    4.84    4.08    3.41
Calculated Deflection (mil):     6.75    6.27    5.59    4.85    4.12    3.43
```

Figure 7.9 Output backcalculation results of an FWD file with a rigid pavement using RMS function.



RO-AVCF.txt - Notepad

```
Backcalculation by BackGenetic3D - Output Check
FWD file: 7705912A    Route: SUM 59            Tested on 2012 03 14
Objective Function: AVCF
SEED Moduli MIN (ksi):           100     15      7       7
SEED Moduli MAX (ksi):           10,000  700     70      70
SEED Thickness MIN (in):         9.00    6.00    100.00
SEED Thickness MAX (in):         9.00    6.00    100.00
--------------------------------------------------------------------------------
Station    2.529LEFT
Load Average (lbf):              12,488
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     5,601   253     11      36
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.69    6.20    5.46    4.65    3.82    3.11
Calculated Deflection (mil):     6.69    6.17    5.46    4.70    3.97    3.31
--------------------------------------------------------------------------------
Station    2.490LEFT
Load Average (lbf):              12,503
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     5,333   238     13      39
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.16    5.67    4.91    4.11    3.35    2.71
Calculated Deflection (mil):     6.16    5.63    4.91    4.18    3.49    2.87
--------------------------------------------------------------------------------
Station    2.438LEFT
Load Average (lbf):              12,452
Layer No:                        1       2       3       Half-space
BackCalculated Moduli (ksi):     7,219   115     8       64
BackCalculated Thickness (in):   9.00    6.00    100.00
Sensor Distnace (in):            0       12      24      36      48      60
Measured Deflection (mil):       6.75    6.31    5.59    4.84    4.08    3.41
Calculated Deflection (mil):     6.75    6.29    5.61    4.87    4.13    3.44
```

Figure 7.10 Output backcalculation results of an FWD file with a rigid pavement using AVCF function.

```
FO-RMS.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Output Check
FWD file: 2507112A    Route: FRA /DEL 71        Tested on 2012 04 10
Objective Function: RMS
SEED Moduli MIN (ksi):            100      15       7       7
SEED Moduli MAX (ksi):            5,000    700      200     200
SEED Thickness MIN (in):          17.00    9.00     100.00
SEED Thickness MAX (in):          17.00    9.00     100.00
--------------------------------------------------------------------------------
Station   28.760Left
Load Average (lbf):               9,881
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      867      47       44      143
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        3.10     2.15     1.60    1.24    0.94    0.73
Calculated Deflection (mil):      3.11     2.12     1.63    1.25    0.95    0.71
--------------------------------------------------------------------------------
Station   28.810Left
Load Average (lbf):               9,852
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      1,021    83       35      199
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        2.85     2.11     1.61    1.24    0.94    0.74
Calculated Deflection (mil):      2.87     2.03     1.61    1.27    0.98    0.75
--------------------------------------------------------------------------------
Station   28.850Left
Load Average (lbf):               9,789
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      1,121    95       42      139
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        2.60     1.85     1.46    1.17    0.90    0.72
Calculated Deflection (mil):      2.60     1.84     1.47    1.17    0.91    0.71
1
```

Figure 7.11 Output backcalculation results of an FWD file with a flexible pavement using RMS function.

```
FO-AVCF.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Output Check
FWD file: 2507112A    Route: FRA /DEL 71        Tested on 2012 04 10
Objective Function: AVCF
SEED Moduli MIN (ksi):            100      15       7       7
SEED Moduli MAX (ksi):            5,000    700      200     200
SEED Thickness MIN (in):          17.00    9.00     100.00
SEED Thickness MAX (in):          17.00    9.00     100.00
--------------------------------------------------------------------------------
Station   28.760Left
Load Average (lbf):               9,881
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      840      130      36      145
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        3.10     2.15     1.60    1.24    0.94    0.73
Calculated Deflection (mil):      3.10     2.10     1.66    1.31    1.02    0.78
--------------------------------------------------------------------------------
Station   28.810Left
Load Average (lbf):               9,852
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      1,150    15       53      154
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        2.85     2.11     1.61    1.24    0.94    0.74
Calculated Deflection (mil):      2.85     2.08     1.65    1.28    0.97    0.73
--------------------------------------------------------------------------------
Station   28.850Left
Load Average (lbf):               9,789
Layer No:                         1        2        3       Half-space
BackCalculated Moduli (ksi):      1,151    26       81      65
BackCalculated Thickness (in):    17.00    9.00     100.00
Sensor Distnace (in):             0        12       24      36      48      60
Measured Deflection (mil):        2.60     1.85     1.46    1.17    0.90    0.72
Calculated Deflection (mil):      2.60     1.85     1.47    1.16    0.92    0.73
```

Figure 7.12 Output backcalculation results of an FWD file with a flexible pavement using AVCF function.

```
CO-RMS.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Output Check
FWD file: 1842212A    Route: CUY 422           Tested on 2012 03 27
Objective Function: RMS
SEED Moduli MIN (ksi):            50      1,000   10      7       7
SEED Moduli MAX (ksi):            5,000   10,000  700     200     200
SEED Thickness MIN (in):          4.00    9.00    6.00    50.00
SEED Thickness MAX (in):          4.00    9.00    6.00    50.00
-------------------------------------------------------------------------------
Station   14.058Righ
Load Average (lbf):               14,500
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      1,817   6,675   244     18      102
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        3.45    2.96    2.57    2.15    1.74    1.40
Calculated Deflection (mil):      3.45    2.96    2.57    2.15    1.75    1.40
-------------------------------------------------------------------------------
Station   14.312Righ
Load Average (lbf):               14,398
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      4,259   4,103   17      7       197
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        4.58    4.19    3.71    3.16    2.59    2.06
Calculated Deflection (mil):      4.60    4.16    3.67    3.14    2.61    2.12
-------------------------------------------------------------------------------
Station   14.371Righ
Load Average (lbf):               14,464
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      3,334   3,386   107     14      116
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        3.94    3.45    2.96    2.43    1.95    1.56
Calculated Deflection (mil):      3.95    3.45    2.95    2.44    1.97    1.55
```

Figure 7.13 Output backcalculation results of an FWD file with a composite pavement using RMS function .

```
CO-AVCF.txt - Notepad
File  Edit  Format  View  Help
Backcalculation by BackGenetic3D - Output Check
FWD file: 1842212A    Route: CUY 422           Tested on 2012 03 27
Objective Function: AVCF
SEED Moduli MIN (ksi):            50      1,000   10      7       7
SEED Moduli MAX (ksi):            5,000   10,000  700     200     200
SEED Thickness MIN (in):          4.00    9.00    6.00    50.00
SEED Thickness MAX (in):          4.00    9.00    6.00    50.00
-------------------------------------------------------------------------------
Station   14.058Righ
Load Average (lbf):               14,500
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      2,514   4,187   113     44      50
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        3.45    2.96    2.57    2.15    1.74    1.40
Calculated Deflection (mil):      3.45    2.96    2.55    2.15    1.79    1.49
-------------------------------------------------------------------------------
Station   14.312Righ
Load Average (lbf):               14,398
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      3,286   5,072   115     10      62
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        4.58    4.19    3.71    3.16    2.59    2.06
Calculated Deflection (mil):      4.58    4.15    3.71    3.22    2.74    2.29
-------------------------------------------------------------------------------
Station   14.371Righ
Load Average (lbf):               14,464
Layer No:                         1       2       3       4       Half-space
BackCalculated Moduli (ksi):      3,901   3,041   111     15      105
BackCalculated Thickness (in):    4.00    9.00    6.00    50.00
Sensor Distnace (in):             0       12      24      36      48      60
Measured Deflection (mil):        3.94    3.45    2.96    2.43    1.95    1.56
Calculated Deflection (mil):      3.94    3.45    2.95    2.45    1.98    1.57
```

Figure 7.14 Output backcalculation results of an FWD file with a composite pavement using AVCF function.

Table 7.4 Calculation time and backcalculated moduli with two different genetic parameters.

	TIME (sec)											
	150 - 60 (Population size and number of generations)						**500 - 100** (Population size and number of generations)					
	R1	R2	F1	F2	C1	C2	R1	R2	F1	F2	C1	C2
1	0.6	1.3	3.9	3.8	0.9	0.5	0.7	4.1	21.5	8.1	6.5	5
2	0.6	0.8	4	3.8	1.2	4.6	0.7	4	21.6	10.7	7.2	2.8
3	0.6	2.2	3.9	3.8	0.8	1.2	1.3	2.1	21.9	14.1	1.2	3.8
4	0.6	1.4	4	3.9	3.2	4.6	1.7	2.9	21.5	3.8	0.7	3.5
5	0.6	1.1	4.2	3.9	2	1.3	1.3	3.4	21.6	20.9	1.9	6.5
6	0.7	0.8	3.9	3.1	0.9	1.4	1.3	3.8	21.8	8.3	2.8	4.3
7	0.7	0.7	4	4	0.8	0.7	1.7	2.3	21.5	20.8	1.9	2.4
8	0.7	3.1	4.1	4	1.8	0.9	1.3	2.9	21.7	3.2	1.6	7.3
9	0.6	1.3	4.1	4	4.7	2.2	1.1	4.1	21.8	12.2	4.4	3.7
10	0.6	1	4.1	3.9	1.8	0.8	0.2	2.3	21.6	11.3	9.7	4.3
Average running time for each calculation (sec)	0.6	1.4	4.0	3.8	1.8	1.8	1.1	3.2	21.7	11.3	3.8	4.4
No. of Stations	34	54	44	52	57	105	34	54	44	52	57	105
Moduli E1 (ksi)	5087	5877	1233	892	1687	1086	5066	5910	1245	899	1683	1097
Moduli E2 (ksi)	32	32	22	21	6959	4192	34	28	15	18	6975	4254
Moduli E3 (ksi)	45	18	25	75	29	31	45	18	26	79	27	25
Moduli E4 (ksi)					50	29					51	30
Average running time for each calculation (sec)	6.3	13.7	40.2	38.2	18.1	18.2	11.3	31.9	216.5	113.4	37.9	43.6
Total Time (min)	3.6	12.3	29.5	33.1	17.2	31.9	6.4	28.7	158.8	98.3	36.0	76.3

CHAPTER 8 CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION

We have presented a detailed study on the backcalculation of pavement layer elastic modulus and thickness using *BackGenetic3D*, a program developed by the University of Akron's Computer Modeling and Simulation Group. The importance of the measurement errors is illustrated clearly by real pavement examples. Besides RMS, an efficient and accurate objective function, called AVCF, is proposed for accurate backcalculation of pavement modulus and thickness. The accuracy of the backcalculated results from these two functions are analyzed and compared. While RMS is sensitive to measurement errors, AVCF is found to be very accurate even when there are measurement errors. Thus, this new function AVCF could be remarkably helpful in future backcalculation of pavement properties. RMS is a commonly used goodness-of-fit function in existing backcalculation procedures. However, backcalculated results based on RMS can be very sensitive to measurement errors. It means that even a slight change in measured deflections could result in a dramatic variation in backcalculated layer modulus and thickness. On the other hand, AVCF can make the backcalculated result close to the measured value independent of the backcalculation algorithm used. The proposed backcalculation method is superior to the similar techniques since it can backcalculate the modulus and thickness simultaneously for any number of pavement layers. The new backcalculation method has been incorporated into a simple, user-friendly, comprehensive GUI which could be also utilized for any layered structures in science and engineering.

8.2 RECOMMENDATIONS

The importance of parameters in genetic algorithm on the backcalculation procedure is an interesting topic for the future study. Recently, there are a variety of optimization techniques with several advantages and disadvantages. A comparative study on the merits of these techniques can help us to better understand the moduli optimization in pavement engineering and to improve the backcalculation method. In addition, the current *BackGenetic3D* program assumes linear elastic pavement layers. The nonlinearity of the stresses in the pavement layers should be considered in the backcalculation procedure especially under high surface loads. The software can be developed to consider the thermal effect in the future versions. The improved genetic algorithm in this study can be used in combination with other advanced numerical simulation tools to increase the accuracy and efficiency in backcalculation of pavement properties.

APPENDIX A: DATA MODULES IN INFORMATION MANAGEMENT SYSTEM

A.1 Data Modules in the Information Management System in LTPP

ADM:	Administration
AWS:	Automated Weather Station
CLM:	Climate
DLR:	Data Load Response
GPR:	Ground Penetrating Radar
INV:	Inventory
MNT:	Maintenance
MON:	Monitoring
RHB:	Rehabilitation
SMP:	Seasonal Monitoring Program
SPS:	Specific Pavement Studies
TRF:	Traffic
TST:	Testing

For each option in box 'IMS Module', there are a series of sub-options in box 'Table'. For example, if we select 'Monitoring' from the left box, there will be 33 sub-options in the right box and those are:

MON_DEFL_BUFFER_SHAPE
MON_DEFL_DEV_CONFIG
MON_DEFL_DEV_SENSORS
MON_DEFL_DROP_DATA
MON_DEFL_EST_SENSOR_OFFSET
MON_DEFL_LOC_INFO
MON_DEFL_MASTER
MON_DEFL_TEMP_DEPTH
MON_DEFL_TEMP_VALUES
MON_DIS_AC_REV
MON_DIS_CRCP_REV
MON_DIS_JPCC_FAULT
MON_DIS_JPCC_FAULT_SECT
MON_DIS_JPCC_REV
MON_DIS_LINK
MON_DIS_PADIAS_AC
MON_DIS_PADIAS_JPCC
MON_DIS_PADIAS42_AC
MON_DIS_PADIAS42_CRCP
MON_DIS_PADIAS42_JPCC
MON_DRAIN_CONDITION
MON_DRAIN_INSPECT
MON_DRAIN_MASTER

MON_DROP_SEP
MON_FRICTION
MON_PROFILE_DATA
MON_PROFILE_MASTER
MON_PUT_DEPTH_POINT
MON_T_PROF_CROSS_SLOPE
MON_T_PROF_INDEX_POINT
MON_T_PROF_INDEX_SECTION
MON_T_PROF_MASTER
MON_T_PROF_PROFILE

A.2 Obtained Information from LTPP Database

File Name	Data Type	
Test Date	Date	
STATE CODE	NUMBER	(2,0)
SHRP ID	VARCHAR2	(4)
DEFL UNIT ID	VARCHAR2	(12)
POINT LOC	NUMBER	(4,1)
DROP NO	NUMBER	(2,0)
TEST TIME	VARCHAR2	(4)
LANE NO	VARCHAR2	(2)
PEAK DEFL 4	NUMBER	(4,0)
DROP HEIGHT	VARCHAR2	(1)
DROP LOAD	NUMBER	(6,0)
DTE	NUMBER	(5,2)
HISTORY STORED	VARCHAR2	(1)
NON DECREASING DEFL	VARCHAR2	(1)
PEAK DEFL 1	NUMBER	(4,0)
CONSTRUCTION NO	NUMBER	(2,0)
PEAK DEFL 3	NUMBER	(4,0)
PEAK DEFL 5	NUMBER	(4,0)
PEAK DEFL 6	NUMBER	(4,0)
PEAK DEFL 7	NUMBER	(4,0)
PEAK DEFL 8	NUMBER	(4,0)
PEAK DEFL 9	NUMBER	(4,0)
RECORD STATUS	VARCHAR2	(1)
PEAK DEFL 2	NUMBER	(4,0)

APPENDIX B: PAVEMENT STRUCTURES OF HIGHWAY SECTIONS IN OHIO

Table B.1 Pavement structures of highway sections in the State of Ohio

Code Number	Layer material and thickness
39-0101-1	Original surface layer AC 1.9 inch
	AC layer below surface 5.1 in
	Base layer GB 8 in
	Subgrade SS
39-0102-1	Original surface layer AC 1.8 inch
	AC layer below surface 2.1 inch
	Base layer GB 11.8 inch
	Subgrade SS
39-0103-1	Original surface layer AC 1.8 inch
	AC layer below surface 2.2 in
	Base layer TB 8 inch
	Subgrade SS
39-0104-1	Original surface layer PC 11.1 inch
	Base layer GB 5.8 in
	Embankment layer GS 16 inch
	Subgrade SS
39-0105-1	Original surface layer AC 1.9 inch
	AC layer below surface 2.1 inch
	Base layer TB 3.8 inch
	Base layer GB 4 inch
	Subgrade SS
39-0105-2	Original surface layer AC 1.9 inch
	AC layer below surface 2.1 inch
	Base layer TB 3.8 inch
	Base layer GB 4 inch
	Subgrade SS
39-0106-1	Original surface layer AC 1.7 inch
	AC layer below surface 5 inch
	Base layer TB 7.9 inch
	Base layer GB 3.8 inch
	Subgrade SS
39-0107-1	Original surface layer AC 1.7 inch
	AC layer below surface 2.1 inch
	Base layer TB 4 inch
	Base layer GB 4.1 inch
	Subgrade SS
39-0108-1	Original surface layer AC 1.7 inch
	AC layer below surface 4.9 inch
	Base layer TB 4 inch

	Base layer GB 8 inch
	Subgrade SS
39-0109-1	Original surface layer AC 1.8 inch
	AC layer below surface 5.2 inch
	Base layer TB 3.9 inch
	Base layer GB 12 inch
	Subgrade SS
39-0110-1	Original surface layer AC 1.8 inch
	AC layer below surface 5.5 inch
	Base layer TB 3.7 inch
	Base layer TB 3.9 inch
	Subgrade SS
39-0111-1	Original surface layer 1.7 inch
	AC layer below surface 2.3 inch
	Base layer TB 7.8 inch
	Base layer TB 4.3 inch
	Subgrade SS
39-0112-1	Original surface layer 1.7 inch
	AC layer below surface 2.3 inch
	Base layer TB 11.8 inch
	Base layer TB 4 inch
	Subgrade SS
39-0159-1	Original surface layer 1.7 inch
	AC layer below surface 2.3 inch
	Base layer GB 4 inch
	Subgrade SS
39-0159-2	Original surface layer 1.7 inch
	AC layer below surface 2.3 inch
	Base layer GB 4 inch
	Subgrade SS
39-0160-1	Original surface layer AC 1.7 inch
	AC layer below surface 2.3 inch
	Base layer TB 11 inch
	Base layer GB 4 inch
	Subgrade SS
39-0201-1	Original surface layer PC 7.9 inch
	Base layer GB 6.2 inch
	Subgrade SS
39-0202-1	Original surface layer PC 8.3 inch
	Base layer GB 5.8 inch
	Subgrade SS
39-0203-1	Original surface layer PC 10.8 inch
	Base layer GB 6.2 inch
	Subgrade SS
39-0204-1	Original surface layer PC 11.1 inch

	Base layer GB 5.8 inch
	Embankment layer GS 16 inch
	Subgrade SS
39-0205-1	Original surface layer PC 8 inch
	Base layer TB 6.2 inch
	Subgrade SS
39-0206-1	Original surface layer PC 7.9 inch
	Base layer TB 5.9 inch
	Subgrade SS
39-0207-1	Original surface layer 11 inch
	Base layer TB 6.2 inch
	Subgrade SS
39-0208-1	Original surface layer PC 10.9 inch
	Base layer TB 6.3 inch
	Subgrade SS
39-0209-1	Original surface layer PC 8.1 inch
	Base layer TB 4 inch
	Base layer GB 4.1 inch
	Subgrade SS
39-0210-1	Original surface layer PC 8 inch
	Base layer TB 4.1 inch
	Base layer GB 3.8 inch
	Subgrade SS
39-0211-1	Original surface layer PC 11.3 inch
	Base layer TB 3.9 inch
	Base layer GB 4 inch
	Subgrade SS
39-0212-1	Original surface layer PC 10.6 inch
	Base layer TB 4.4 inch
	Base layer GB 3.9 inch
	Embankement layer GS 15 inch
	Subgrade SS
39-0259-1	Original surface layer PC 10.9 inch
	Base layer 6.3 inch
	Embankement 18 GS inch
	Subgrade SS
39-0260-1	Original surface layer PC 11.3 inch
	Base layer TB 4 inch
	Base layer GB 4.1 inch
	Embankment layer GS 18 inch
	Subgrade SS
39-0261-1	Original surface layer PC 11 inch
	Base layer TB 4.2 inch
	Base layer GB 4.3 inch
	Subgrade SS

39-0262-1	Original surface layer PC 11.1 inch
	Base layer TB 4.1 inch
	Base layer GB 4.1 inch
	Subgrade SS
39-0263-1	Original surface layer PC 11 inch
	Base layer GB 6.2 inch
	Subgrade SS
39-0264-1	Original surface layer PC 11.6 inch
	Base layer TB 4 inch
	Base layer GB 6 inch
	Subgrade SS
39-0265-1	Original surface layer PC 11.2 inch
	Base layer TB 3.8 inch
	Base layer GB 4 inch
	Embankment layer GS 30 inch
	Subgrade SS
39-0809-1	Original surface layer PC 7.9 inch
	Base layer GB 6.1 inch
	Embankment layer GS 24 inch
	Subgrade SS
39-0810-1	Original surface layer PC 11 inch
	Base layer GB 6.1 inch
	Embankment layer GS 36 inch
	Subgrade SS
39-0901-1	Original surface layer AC 1.7 inch
	AC layer below surface 2.1 inch
	Base layer TB 12.1 inch
	Subbase layer TS 3.8 inch
	Subbase layer GS 6 inch
	Embankment layer GS 12 inch
	Subgrade SS
39-0902-1	Original surface layer AC 1.8 inch
	AC layer below surface 2.3 inch
	Base layer TB 12 inch
	Subbase layer TS 3.7 inch
	Subbase layer GS 6 inch
	Subgrade SS
39-0903-1	Original surface layer AC 1.8 inch
	AC layer below surface 2.2 inch
	Base layer TB 12 inch
	Subbase layer TS 4 inch
	Subbase layer GS 6 inch
	Subgrade SS
39-3013-1	Original surface layer PC 8.3 inch
	Base layer TB 4 inch

	Subgrade SS
39-3013-2	Over layer AC 1.8 inch
	AC layer surface 1.9 inch
	Original surface layer PC 8.3 inch
	Base layer TB 4 inch
	Subgrade SS
39-3801-1	Original surface layer PC 9.2 inch
	Base layer TB 4.4 inch
	Subgrade SS 100 inch
39-4018-1	Original surface layer PC 10.3 inch
	Base layer TB 3.6 inch
	Subgrade SS
39-4018-2	Original surface layer PC 10.3 inch
	Base layer TB 3.6 inch
	Subgrade SS
39-4018-3	Over layer AC 1.5 inch
	AC layer below surface 2 inch
	Original surface layer PC 10.3 inch
	Base layer TB 3.6 inch
	Subgrade SS
39-4031-1	Original surface layer PC 9.2 inch
	Base layer GB 6.1 inch
	Subgrade SS
39-5003-1	Original surface layer PC 9.7 inch
	Base layer TB 4.6 inch
	Subbase layer GS 5.2 inch
	Subgrade SS
39-5010-1	Original surface layer PC 8.8 inch
	Base layer TB 5 inch
	Subgrade SS
39-5010-2	Over layer AC 2.8 inch
	Original surface layer PC 8.8 inch
	Base layer TB 5 inch
	Subgrade SS
39-5010-3	Surface treatment layer AC 0.5 inch
	Over layer AC 2.8 inch
	Original surface layer PC 8.8 inch
	Base layer TB 5 inch
	Subgrade SS
39-5010-4	Surface treatment layer AC 0.5 inch
	Over layer AC 2.8 inch
	Original surface layer PC 8.8 inch
	Base layer TB 5 inch
	Subgrade SS
39-5569-1	Over layer PC 8.3 inch

	Inter layer AC 0.7 inch
	Original surface layer PC 8 inch
	Base layer TB 5.9 inch
	Subgrade SS
39-7021-1	Over layer AC 1.2 inch
	AC layer below surface 1.4 inch
	Original surface layer PC 9 inch
	Base layer GB 6 inch
	Subgrade SS
39-7021-2	Over layer AC 3.3 inch
	Over layer AC 0 inch
	AC layer below surface 1.4 inch
	Original surface layer PC 9 inch
	Base layer GB 6 inch
	Subgrade SS
39-9006-1	Over layer PC 9.4 inch
	Inter layer AC 1.2 inch
	Original surface layer PC 8.8 inch
	Base layer GB 6.8 inch
	Subgrade SS
39-9006-2	Over layer PC 9.4 inch
	Inter layer AC 1.2 inch
	Original surface layer PC 8.8 inch
	Base layer GB 6.8 inch
	Subgrade SS
39-9006-3	Over layer PC 9.4 inch
	Inter layer AC 1.2 inch
	Original surface layer PC 8.8 inch
	Base layer GB 6.8 inch
	Subgrade SS
39-9022-1	Over layer PC 10.6 inch
	Inter layer AC 1 inch
	Original surface layer PC 8.7 inch
	Base layer TB 4.4 inch
	Subgrade SS
39-9022-2	Over layer PC 10.6 inch
	Inter layer AC 1 inch
	Original surface layer PC 8.7 inch
	Base layer TB 4.4 inch
	Subgrade SS
39-A410-1	Original surface layer PC 10.1 inch
	Base layer TB 4.2 inch
	Subgrade SS
39-A410-2	Original surface layer PC 10.1 inch
	Base layer TB 4.2 inch

	Subgrade SS
39-A411-1	Original surface layer PC 10.2 inch
	Base layer TB 4.1 inch
	Subgrade SS
39-A411-2	Original surface layer PC 10.2 inch
	Base layer TB 4.1 inch
	Subgrade SS
39-A412-1	Original surface layer PC 10.3 inch
	Base layer TB 3.6 inch
	Subgrade SS
39-A412-2	Original surface layer PC 10.3 inch
	Base layer TB 3.6 inch
	Subgrade SS
39-A430-1	Original surface layer PC 10.2 inch
	Base layer TB 4.8 inch
	Subgrade SS
39-A430-1	Original surface layer PC 10.2 inch
	Base layer TB 4.8 inch
	Subgrade SS
39-B410-1	Original surface layer PC 9.1 inch
	Base layer TB 4.5 inch
	Subgrade SS
39-B410-2	Original surface layer PC 9.1 inch
	Base layer TB 4.5 inch
	Subgrade SS
39-B411-1	Original surface layer PC 9.1 inch
	Base layer TB 4.3 inch
	Subgrade SS
39-B411-2	Original surface layer PC 9.1 inch
	Base layer TB 4.3 inch
	Subgrade SS
39-B412-1	Original surface layer PC 9 inch
	Base layer TB 4.2 inch
	Subgrade SS
39-B412-2	Original surface layer PC 9 inch
	Base layer TB 4.2 inch
	Subgrade SS
39-B430-1	Original surface layer PC 8.7 inch
	Base layer TB 4.6 inch
	Subgrade SS
39-B430-2	Original surface layer PC 8.7 inch
	Base layer TB 4.6 inch
	Subgrade SS

APPENDIX C: PROCEDURES OF LOADING LTPP PROGRAM TO EXCEL

C.1 For Microsoft Excel 2003

1. Extract and download the MON_DEFL_DROP_DATA as Excel file from LTPP website.
2. Open the Excel file, go to Tools | Add-Ins | Browse, and find the folder where the "LTPP TOOL.xla" file is being placed. Choose the file "LTPP TOOL.xla" and click OK.
3. There is a new menu "LTPP TOOL" loaded on the menu bar of Excel window.
4. Click the menu "LTPP TOOL". The program will be started.
5. To unload the tool from Excel, go to Tools | Add-Ins, and uncheck the option "LTPP Tool". Click “OK”.

C.2 For Microsoft Excel 2007

1. Extract and download the MON_DEFL_DROP_DATA as Excel file from LTPP website.
2. Open the Excel file, go to Office Button | Excel Options | Add-Ins, and select “Excel Add-ins” from the “Manage” Combobox at the bottom of the page. Click on Go | Browse, and find the folder where the "LTPP TOOL.xla" file is located. Choose the file "LTPP TOOL.xla" and click OK.
3. There is a new menu "Add-Ins" loaded on the menu bar of Excel window.
4. Click on Add-Ins | LTPP TOOL, and the program will start.
5. To unload the tool from Excel, go to Office Button | Excel Options | Add-Ins, and select the “Excel Add-ins” from the “Manage” Combobox at the bottom of the page. Click on Go and uncheck the option "LTPP Tool". Click “OK”.

APPENDIX D: VBA CODE FOR DEFLECTION DATA SCREENING

```
Sub defl_390101()
Dim idx(150) As Integer
For Each Sheet In Sheets
  If Sheet.Name <> "MON_DEFL_DROP_DATA" Then
    Application.DisplayAlerts = False
    Sheet.Delete
    Application.DisplayAlerts = True
  End If
Next
For i = 1 To 24
  If (Cells(1, i) = "LANE_NO") Then
    lane_no = i
  ElseIf (Cells(1, i) = "DROP_HEIGHT") Then
    drop_height = i
  ElseIf (Cells(1, i) = "DROP_NO") Then
    drop_no = i
  ElseIf (Cells(1, i) = "PEAK_DEFL_1") Then
    peak_defl_1 = i
  ElseIf (Cells(1, i) = "PEAK_DEFL_7") Then
    peak_defl_7 = i
  ElseIf (Cells(1, i) = "POINT_LOC") Then
    point_loc = i
  ElseIf (Cells(1, i) = "DROP_LOAD") Then
    drop_load = i
  ElseIf (Cells(1, i) = "TEST_DATE") Then
    test_date = i
  End If
Next
k = 0
Sheets.Add.Name = "sheet1"
nrow = UsedRange.Rows.Count
For i = 2 To nrow
  If (Cells(i, lane_no) = "F1" And Cells(i, drop_height) = "4") Then
    k = k + 1
    Sheets("sheet1").Cells(k, 1) = i
    Sheets("sheet1").Cells(k, 2) = Cells(i, test_date)
    Sheets("sheet1").Cells(k, 3) = Cells(i, lane_no)
    Sheets("sheet1").Cells(k, 4) = Cells(i, drop_height)
    Sheets("sheet1").Cells(k, 5) = Cells(i, drop_no)
    Sheets("sheet1").Cells(k, 6) = Cells(i, point_loc)
    Sheets("sheet1").Cells(k, 7) = Cells(i, peak_defl_1) * 550 / Cells(i, drop_load)
    Sheets("sheet1").Cells(k, 8) = Cells(i, peak_defl_7) * 550 / Cells(i, drop_load)
  End If
Next
```

```
Sheets("sheet1").Columns(2).NumberFormat = "m/d/yyyy"
nrow = Sheets("sheet1").UsedRange.Rows.Count
Sheets.Add.Name = "result"
For i = 1 To nrow
  If (idx(i) = 0) Then
    Sheets("result").Cells(i, 1) = Sheets("sheet1").Cells(i, 2)
    Sheets("result").Cells(i, 2) = Sheets("sheet1").Cells(i, 3)
    Sheets("result").Cells(i, 3) = Sheets("sheet1").Cells(i, 4)
    Sheets("result").Cells(i, 4) = Sheets("sheet1").Cells(i, 6)
    Sheets("result").Cells(i, 5) = Sheets("sheet1").Cells(i, 7)
    Sheets("result").Cells(i, 6) = Sheets("sheet1").Cells(i, 8)
    idx(i) = 1
    k = 1
    For j = i + 1 To nrow
      If  (Sheets("sheet1").Cells(i, 2) = Sheets("sheet1").Cells(j, 2) And Sheets("sheet1").Cells(i, 6) = Sheets("sheet1").Cells(j, 6)) Then
        Sheets("result").Cells(i, 5) = Sheets("result").Cells(i, 5) + Sheets("sheet1").Cells(j, 7)
        Sheets("result").Cells(i, 6) = Sheets("result").Cells(i, 6) + Sheets("sheet1").Cells(j, 8)
        k = k + 1
        idx(j) = 1
      End If
    Next
    Sheets("result").Cells(i, 5) = Sheets("result").Cells(i, 5) / k
    Sheets("result").Cells(i, 6) = Sheets("result").Cells(i, 6) / k
  End If
Next
Sheets("result").UsedRange.SpecialCells(4).EntireRow.Delete
Sheets("result").Columns(1).NumberFormat = "m/d/yyyy"
End Sub
```

APPENDIX E: LOADING VBA CODE

The following steps can be applied to the load data:

1. Open the downloaded *.xls* format data file.
2. Click on Tools | Macro | Visual Basic Editor.
3. Double click on the sheet named "MON_DEFL_DROP-DATA" in the window of "Project explorer".
4. Click Insert | File, select the code DATA_SCREENING, and click on Open button.
5. Determine the filtering conditions and modify the corresponding code as stated in the text.
6. Click Run | Run Sub/UserForm or press F5. Two new sheets will be created: "sheet1" and "results", in which the normal data together with averaged deflection data are respectively stored.

APPENDIX F: VBA CODE FOR OVERLAY

F.1: Code in "This Workbook"

```
Private Sub Workbook_AddinInstall()
   On Error Resume Next
   With Application.CommandBars(1).Controls.Add(Type:=msoControlPopup)
      .Caption = "OVERLAY"
      .OnAction = "Overfwd"
   End With
End Sub

Private Sub Workbook_AddinUninstall()
   On Error Resume Next
   Dim ctl As CommandBarControl
   'Application.CommandBars("mycommandbar").Delete
   For Each ctl In Application.CommandBars(1).Controls
      If ctl.Caption = "OVERLAY" Then ctl.Delete
   Next ctl
End Sub
```

F.2: Instruction for Loading and Unloading the Overlay Software

F.2.1 For Microsoft Excel 2003

- Open the Excel file, go to Tools | Add-Ins | Browse, and find the folder where the "OVERLAY.xla" file is being placed. Choose the file "OVERLAY.xla" and click OK.
- There is a new menu "OVERLAY" loaded on the menu bar of Excel window.
- Click on the menu "OVERLAY", and the program will start.
- To unload the tool from Excel, go to Tools | Add-Ins and uncheck the option "Overlay". Click "OK".

F.2.2 For Microsoft Excel 2007

- Open the Excel file, go to Office Button | Excel Options | Add-Ins, and select the "Excel Add-ins" from the "Manage" Combobox at the bottom of the page. Click on Go | Browse, and find the folder where the "OVERLAY.xla" file is located. Choose the file "OVERLAY.xla" and click OK.
- There is a new menu "Add-Ins" loaded on the menu bar of Excel window.
- Click on Add-Ins | OVERLAY, and the program will start.

- To unload the tool from Excel, go to Office Button | Excel Options | Add-Ins, and select the "Excel Add-ins" from the "Manage" Combobox at the bottom of the page. Click Go and uncheck the option "Overlay". Click "OK".

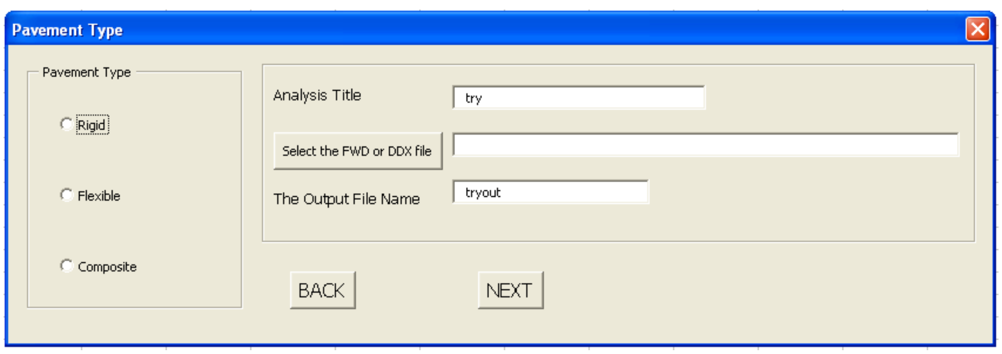
F.3: Code in "UserForms"

UserForm1 "Welcome":

UserForm "Welcome"

```
Private Sub CommandButton1_Click()
Unload Me
UserForm2.Show
End Sub
```

UserForm2 "Pavement Type":

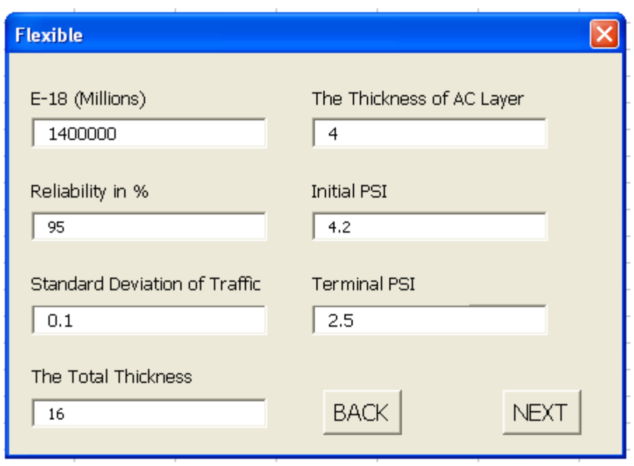


UserForm "Pavement Type"

```
Private Sub CommandButton1_Click()
On Error Resume Next
If OptionButton1.Value = True Then
UserForm2.Hide
UserForm5.Show
End If
If OptionButton2.Value = True Then
UserForm2.Hide
UserForm3.Show
```

```
End If
If OptionButton3.Value = True Then
UserForm2.Hide
UserForm4.Show
End If
End Sub

Private Sub CommandButton3_Click()
Unload Me
UserForm1.Show
End Sub
Private Sub CommandButton4_Click()
filetoopen = Application.GetOpenFilename("FWD Files (*.FWD), *.FWD, DDX File
(*.DDX),*.DDX, All Files (*.*),*.*")
If filetoopen <> False Then
   TextBox10.Value = filetoopen
End If
End Sub

Private Sub UserForm_initialize()
TextBox1.Value = "try"
TextBox15.Value = "tryout"
End Sub
```

UserForm3 “Flexible”:

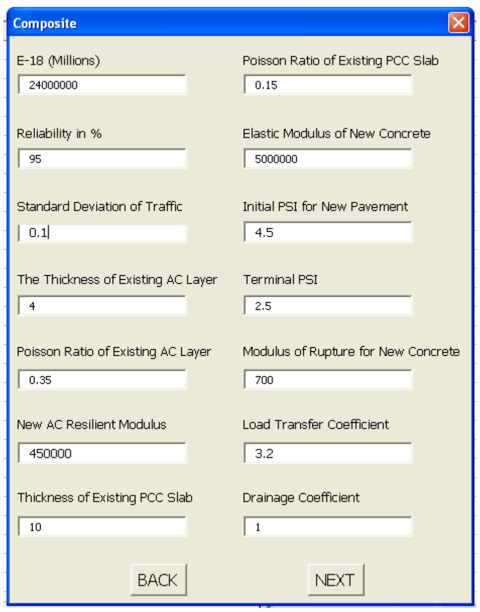


UserForm “Flexible”

```
Private Sub CommandButton2_Click()
Option1 = 2
Call MAIN
Unload Me
UserForm6.Show
End Sub
```

```
Private Sub CommandButton3_Click()
Unload Me
UserForm2.Show
End Sub
Private Sub UserForm_initialize()
TextBox14.Value = 1400000
TextBox11.Value = 95
TextBox4.Value = 0.1
TextBox5.Value = 16
TextBox13.Value = 4
TextBox9.Value = 4.2
TextBox16.Value = 2.5
End Sub
```

UserForm4 “Composite”:

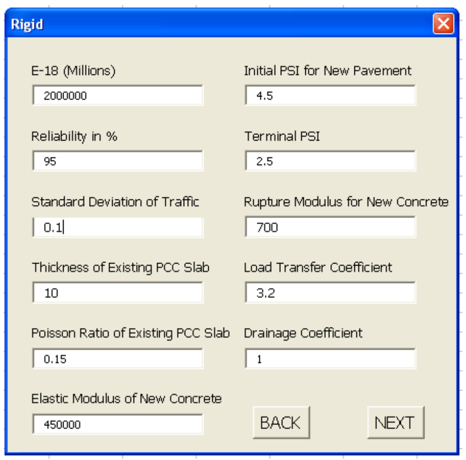


UserForm “Composite”

```
Public Sub CommandButton2_Click()
Option1 = 3
Call MAIN
Unload Me
UserForm6.Show
End Sub

Private Sub CommandButton3_Click()
Unload Me
UserForm2.Show
End Sub
```

```
Private Sub UserForm_initialize()
TextBox25.Value = 24000000
TextBox24.Value = 95
TextBox4.Value = 0.1
TextBox5.Value = 4
TextBox13.Value = 0.35
TextBox12.Value = 450000
TextBox8.Value = 10
TextBox9.Value = 0.15
TextBox19.Value = 5000000
TextBox18.Value = 4.5
TextBox17.Value = 2.5
TextBox16.Value = 700
TextBox20.Value = 3.2
TextBox21.Value = 1
End Sub
```

UserForm5 “Rigid”:

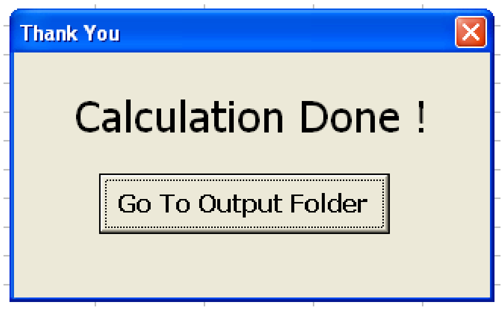


UserForm “Rigid”

```
Private Sub CommandButton2_Click()
Option1 = 1
Call MAIN
Unload Me
UserForm6.Show
End Sub

Private Sub CommandButton3_Click()
Unload Me
UserForm2.Show
End Sub
```

```
Private Sub UserForm_initialize()
TextBox14.Value = 2000000
TextBox11.Value = 95
TextBox4.Value = 0.1
TextBox5.Value = 10
TextBox19.Value = 700
TextBox18.Value = 3.2
TextBox13.Value = 0.15
TextBox12.Value = 450000
TextBox8.Value = 4.5
TextBox9.Value = 2.5
TextBox17.Value = 1
End Sub
```

UserForm6 “Thank you”:



UserForm “Thank you”

```
Private Sub CommandButton1_Click()
On Error Resume Next
cpath = CurDir
Shell "Explorer.exe /n," & cpath, vbNormalFocus
End
End Sub
```

APPENDIX G: BACKGENETIC3D SUBROUTINES

In the *BackGenetic3D* program code several subroutines and structures are designed to improve the application of the program. It is possible to divide the subroutines into three major sections.

G.1: Basic Functions

The basic functions section consists of several subroutines that help to improve the calculation process. These subroutines are:

1. Bessel function	(*besselj*)
2. Matrix multiplications	(*NumMultiplyMatrix* and *MatrixXMultiply*)
3. Print the matrix	(*PrintMatrix*)
4. Variable exchange	(*Swap* and *Swapul*)
5. Maximum and minimum	(*Max* and *Min*)
6. Random creation	(*NormRnd*)
7. String replacement	(*ReplaceStr*)

G.2: Forward Calculation Subroutines

First of all in the *Backgenetic3D* program, we need to call the forward calculation of the deflections. Since the forward calculation is designed in our team before, the codes are available and can be called in the program as forward calculation subroutines. These subroutines are:

1. Global variables of forward initialization	(*FwdInitGlobalVar*)
2. Data in forward initialization	(*FwdInitData*)
3. Default data in forward calculation	(*FwdDefaultData*)
4. Input data in forward calculation	(*FwdInputData*)
5. Print the initial data of forward calculation	(*FwdPrintInitData*)
6. Matrices in forward calculation	(*FwdCalcMatrixZp* and *FwdCalcMatrixAk*)
7. Forward integrand calculation	(*FwdIntegrand*)
8. Forward integral calculation	(*FwdForwardCalc*)
9. The main forward calculation	(*FwdCalc*)

G.3: Backward Calculation Subroutines

Backward calculations are another part of the main code in *BackGenetic3D* program. The subroutines in this section are mainly based on the improved genetic algorithm which presented below.

1. Genetic algorithm initialization (*GA_Initialize*)
2. Default data in backward calculation (*BwdDefaultData*)
3. Input data in backward calculation (*BwdInputData*)
4. Random value in genetic algorithm (*GA_RandVal*)
5. Fitness calculation in genetic algorithm (*GA_CalcFitness*)
6. Selection process in genetic algorithm (*GA_Select*)
7. Divide intervals in genetic algorithm (*GA_AutoDivideInterval*)
8. Sort fitness values in genetic algorithm (*GA_SortByFitnessVal*)
9. Crossover in genetic algorithm (*GA_CrossOver* and *GA_Xover*)
10. Mutation in genetic algorithm (*GA_Mutate*)
11. Total report (*GA_ReportTtlLog*)
12. Main backward calculation (*BwdCalc*)

In addition to the mentioned subroutines, five different structures have been designed in the program which consist all input information and the corresponding output results:

1. STRU_INPUT_INFO (for input information)
2. STRU_LAY_INFO (for layer information)
3. STRU_SENSOR_INFO (for load and sensor information)
4. STRU_GENO_TYPE (for genetic information)
5. STRU_RESULTS (for output results)

APPENDIX H: INITIAL PARAMETERS

H.1: Basic Parameters

```
MAX_LAY_NUM                    50     // Maximum No. of layers (including the half-space)
MAX_SENSOR_DOT_NUM             50     // Maximum number of sensors
PI              3.14159265358979      // The Pi number
```

H.2: Parameters in Forward Calculation

```
GK_NODES_HALF_GK_NUM           31     // The number of semi-Gauss-Kronrod points
GK_NODES_NUM                   61     // The number of Gauss-Kronrod points
GK_INTERVAL_BEGIN              0      // The lower bound of Gauss-Kronrod integral
GK_INTERVAL_END                35     // The upper bound of Gauss-kronrod integral
```

H.3: Parameters in Backward Calculation

```
GA_POPSIZE            (500)
GA_MAX_GEN            (100)
GA_DIVIDE_GEN         (40)            // Subdivide the search space in every generation
GA_LO                 (0.80)          // Degree of interval volatilization
GA_PXCOVER            (0.98)          // Cross probability
GA_PMUTATION          (0.05)          // Mutation probability
GA_PCOMBINE           (0.05)          // Assemble cross probability
GA_PCHOOSE_BAD        (0.05)          // Probality of selecting the pessimum individual
GA_MIN_ERR            (1e-03)         // Threshold value for GA
GA_ERR_SAME_FITNESS                   (0.01)
GA_BIGGER_THAN_MAX_FITNESS            (10000)
GA_LESS_THAN_MIN_FITNESS              (-10000)
```

APPENDIX I PAVEMENT OVERLAY DESIGN SOFTWARE

I.0 INTRODUCTION

Beginning in 1985, the Ohio Department of Transportation (ODOT) used the deflections collected with Dynaflect as the basis for designing asphalt overlays. A recent ODOT research project, FHWA/OH-2007/014 found the current design procedure is not stable because the deflections measured with Dynaflect were approaching the magnitude of the sensor error. Therefore, it was recommended the deflections be collected with FWD. The FWD test can apply heavier load to obtain larger deflections. This research was to modify the Dynaflect overlay design procedure to use the FWD deflection data. Since the FWD has a different sensor set-up as compared to Dynaflect and the test files also have different data formats, a considerable modification to the previous Fortran code of Dynaflect design was imperative. Moreover, the previous Fortran code was under the DOS environment which doesn't take full advantage of the rapid development in computer technology which lets people run the software more conveniently. For example, in the DOS environment, if the users want to change an input value entered in the previous steps, they have to stop the current running and restart the code from the beginning. Therefore, ODOT advised we design the new FWD procedure as an Excel/VBA based GUI software and keep the similar output formats as the previous Fortran code.

I.1 FWD AND DDX DATA FORMAT

The FWD control program generates data files with the extension FWD or DDX. Both FWD and DDX files have fixed formats. The FWD file generally consists of 36 lines of "Header" information immediately followed by the line of global test information. The global test information, i.e., Line 37 includes county name, district number, test data, route number, route type etc. Test data are stored chronologically from Line 38 to the end of the file and they are in groups of five lines for each test: the line of station identifier, three lines of loads and peak deflections, and one comment line for this test group. The comment is very flexible for tester to record any useful information on the test.

In the current software design, besides all test data, the following data lines in FWD data file are also used in each run:

- Line 3: The radius of the plate and sensor distribution data
- Line 29: No. of sequences stored in the current data file
- Line 37: Global test information

The DDX file is divided into sections each having a bracketed header line. The data is composed of a descriptive name, an equal sign, and the values. Although every value has a descriptive name which let users easily understand the meaning of this value, it is still necessary to generate DDX file with fixed format similar to FWD data because only in this way, either VBA or Fortran could handle the data reading by their line numbers. Similar to the FWD data file, the following data lines in the DDX data file are also used in each run:

- Line 31: The radius of the plate
- Line 33: Sensor distribution data
- Line 47: Global test information
- Line 51: Number of sequences stored in the current data file

I.2 THEORETICAL MODIFICATION FROM DYNAFLECT OVERLAY DESIGN

When transforming the previous Fortran code in Dynaflect overlay design to the current VBA-GUI software of FWD overlay design, there are mainly three places of theoretical modifications as will be stated below. Note that except for the theoretical modifications and the VB graph interface design, the major part of the code was kept as close as possible to the previous one.

I.2.1 COMPOSITE PAVEMENT OVERLAY DESIGN

In the overlay design for composite pavement, before calculating the overlay thickness, the equivalent Young's modulus needs to be determined with the measured deflections which are induced by the falling weights and collected by a sequence of sensors. These sensors are generally distributed along the same line. As shown in Fig. I.1, there are two rotating weights in the Dynaflect test system and these offset 10" from the line of the sensors. Since the theory of backcalculation is generally derived assuming the load and sensors are along the same line, an equivalent set-up is used in the calculation as shown in Fig. I.2. However, in the FWD test system, there is only one load and it is aligned with the sensors (Fig. I.3). Thus the backcalculation theory can be directly applied to FWD design with no need for the equivalent set-up. Moreover, in Dynaflect overlay design, the value of *area* is calculated from the five sensors with distances 0, 12, 24, 36 and 48 in, as shown in Eq. (I.1). Based on the method proposed for the FWD overlay design in Ioannides *et al* (1989), only four sensors are used to calculate the *area* value (Eq. I.2), with distances of 0, 12, 24, and 36 in. The *area-l* relationship proposed in Ioannides *et al* (1989) which is shown as the curve labeled with "ELASTIC SOLID Distributed Load (a = 5.9055 in)" in Fig. I.4 is also different to the one used in Dynaflect design (Chou, 1995). The codes in Dynaflect corresponding to all these points need to be particularly considered and properly modified when developing the FWD code.

$$area_{dyna} = \frac{1}{D(1)}\left[2.81D(1) + 8D(2) + 10.87D(3) + 11.515D(4) + 5.835D(5)\right] \quad \text{Eq. (I.1)}$$

$$area_{fwd} = \frac{1}{D(1)}[6D(1) + 12D(2) + 12D(3) + 6D(4)] \quad \text{Eq. (I.2)}$$

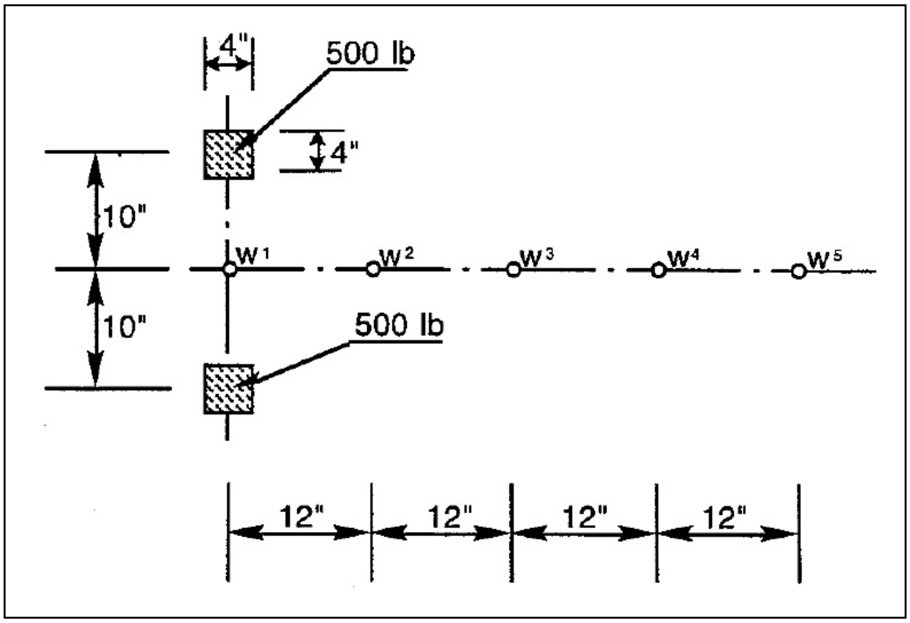


Figure I.1 Real load and sensors distribution in Dynaflect test (Chou, 1995).

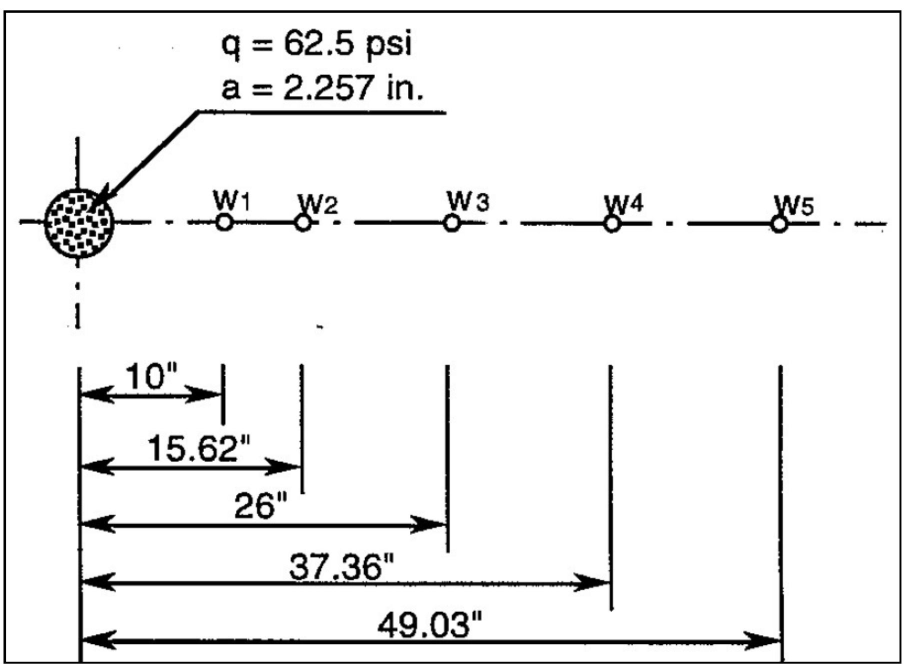


Figure I.2 Equivalent load and sensors distribution in Dynaflect test (Chou, 1995).

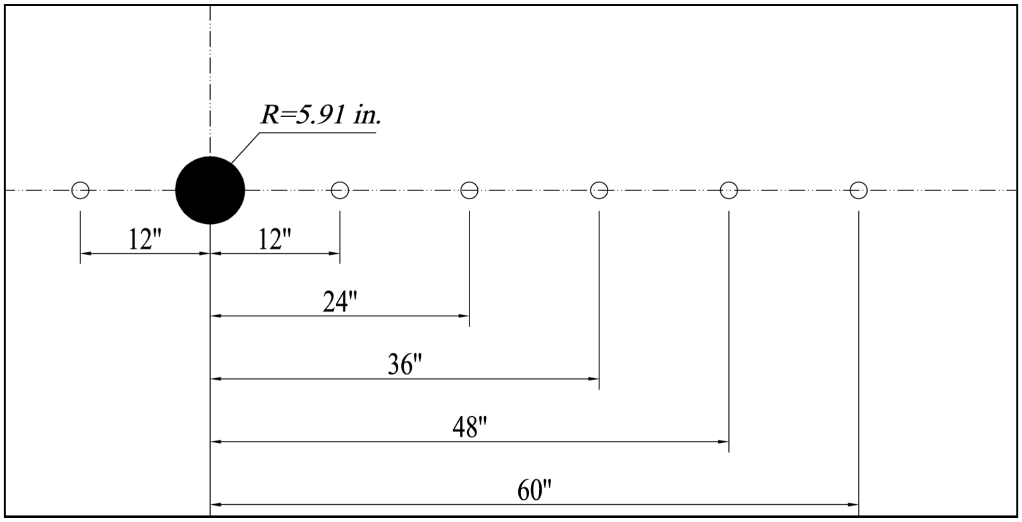


Figure I.3 Load and sensors distribution in FWD test.

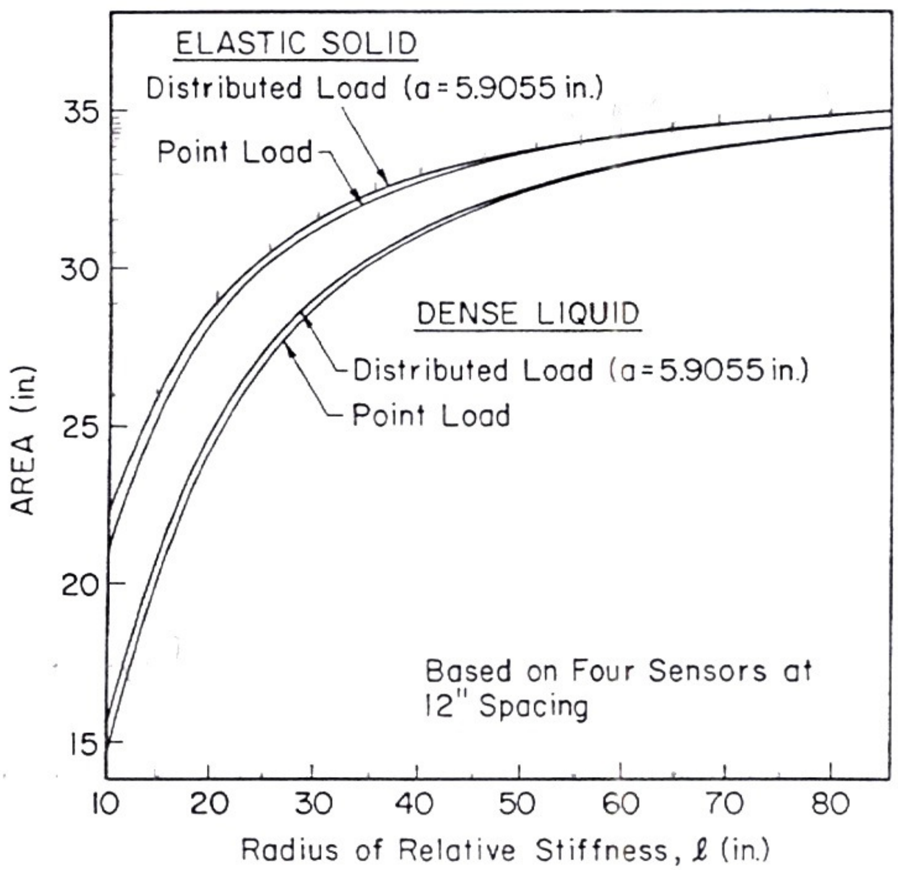


Figure I.4 *Area-l* relation curve for FWD Overlay Design (Ioannides *et al.*, 1989).

I.2.2 FLEXIBLE PAVEMENT OVERLAY DESIGN

In the overlay design for flexible pavement, before calculating the overlay thickness, the subgrade modulus M_R and the effective modulus E_p of the pavement above subgrade both need to be determined.

Equation (I.3) is recommended by AASHTO (1993) for calculating M_R, where P is the load of the falling weight, r is the distance from the sensor to the center of the load, and d_r is the collected deflection at this sensor. AASHTO (1993) indicates the deflection used to backcalculate the subgrade modulus must be measured far away enough so that it provides a good estimate of the subgrade modulus. In the Dynaflect design, the deflection measured from the sensor with distance 48 (equivalent as 49.03 in) was used. We used the deflection measured from 60 in to calculate M_R.

$$M_R = \frac{0.24P}{d_r r} \qquad \text{Eq. (I.3)}$$

For the calculation of the effective modulus E_p in the previous Dynaflect design, a relatively complicated procedure was applied. The linear elastic layer computer program KENLAYER was used to determine the non-dimensional function $F(z)$ which is independent of the pavement modulus. Based on the $F(z)$ function and the determined subgrade modulus M_R and assuming an arbitrary value for E_p, the theoretical deflection at the first sensor was calculated. Applying the trial-and-error method and comparing the calculated deflection at the first sensor with the measured one, the modulus E_p was iteratively determined.

In the current software design, since the falling weight is on the line of sensors and there is an equation in AASHTO (1993) for calculating the theoretical deflection at the first sensor (Eq. I.4), we have considerably simplified the calculation procedure for determining E_p. We directly applied the trial-and-error method while comparing d_0 from Eq. (I.4) with the measured deflection at the first sensor. The modulus E_p is also determined iteratively.

$$d_0 = 1.5pa\left\{ \frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + \frac{\left[1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}\right]}{E_p} \right\} \qquad \text{Eq. (I.4)}$$

where d_0 is the deflection measured at the center of the load plate (and adjusted to a standard temperature of 68℉) in inch, p is the load pressure in psi, a is the load plate radius in inch, D is the total thickness of pavement layers above the subgrade in inch, M_R is the subgrade resilient modulus in psi, and E_p is the effective modulus of all pavement layers above the subgrade in psi.

I.3 NEW DESIGN PROCEDURE

The following steps reflect the changes in design procedure from Dynaflect to FWD. The *italic* contents indicate that this part is exactly the same as in Dynaflect. Similar content could be found in Chou (1995) and Tang (1995).

I.3.1 COMPOSITE PAVEMENT OVERLAY DESIGN PROCEDURE FOR FWD TEST SYSTEM

- Collect the deflection data and produce data file in FWD or DDX format.
- Read the deflection at sensors with distances 0, 12, 24, 36 in. and calculate the area value using Eq. (I.2).
- Determine the radius of the relative stiffness l from the *area-l* relation in Fig. I.4.
- *Determine the non-dimensional deflection at the first sensor.*
- *Calculate E_p and subgrade reaction k.*
- *Calculate the effective modulus of the new combined pavement depth $E_{eff.}$*
- *Calculate the effective thickness of existing pavement $D_{eff.}$*
- *Calculate the required pavement thickness $D_{req.}$*
- *Determine asphalt concrete (AC) overlay thickness.*

The Overlay Design is based on the backcalculation of the effective modulus of the pavement and the deflection data assuming the pavement is composed of a single material. The procedure in Overlay Design for composite pavement can be divided into the following steps:

1. Read the deflection data from FWD or DDX file (Load and sensor distribution is presented in Fig. I.3)
2. Calculate the area value: Calculate the effective thickness D_{eff} if the material is assumed to be Portland cement concrete (PCC)

$$Area_{fwd} = \frac{1}{D(1)}[6D(1) + 12D(2) + 12D(3) + 6D(4)] \qquad \text{Eq. (I.5)}$$

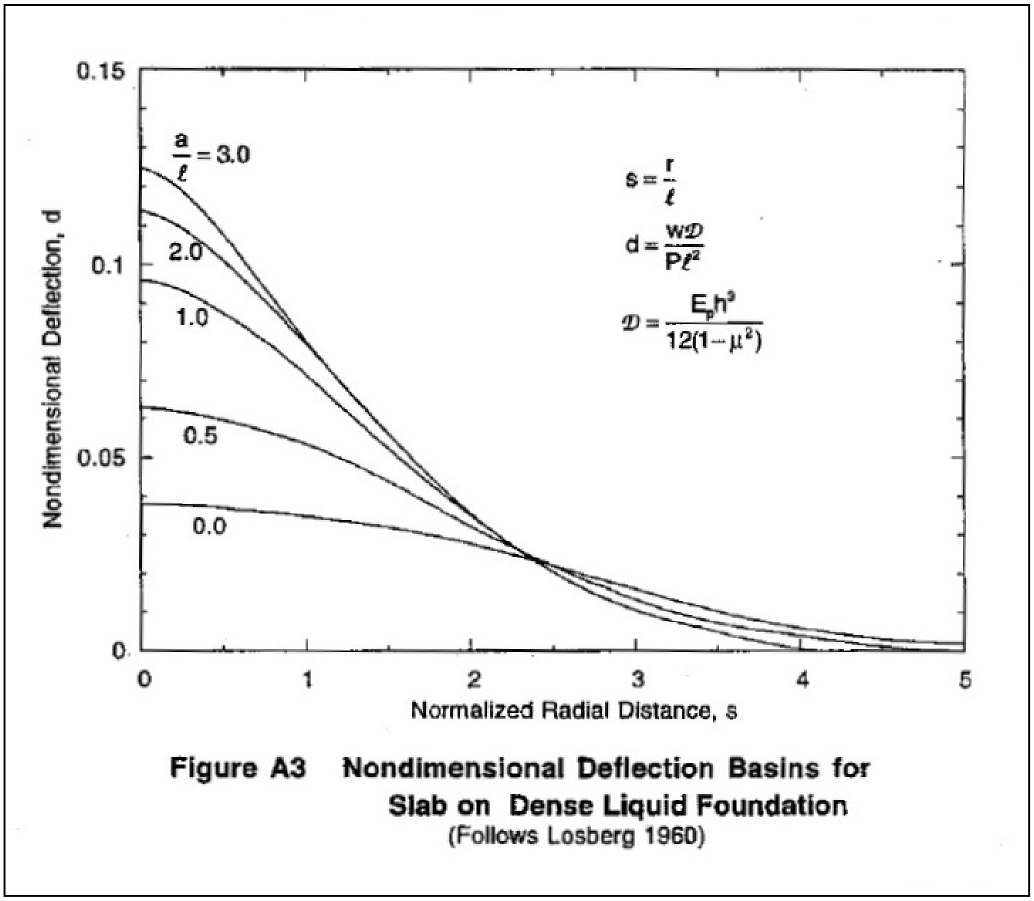


Figure I.5 Nondimensional deflection basins for slab on dense liquid foundation (Chou, 1995).

3. Determine the radius of the relative stiffness: Calculate required PCC overlay thickness using AASHTO method (Fig. I.4)
4. Backcalculate the effective modulus: Calculate the corresponding AC overlay thickness by using AC-PCC ratio (Figs. I.5 and I.6)

$$E_p = \frac{12Pl v^2(1-v^2)}{h^3}\frac{d_1}{w_1} \quad \text{Eq. (I.6)}$$

$$k = \frac{d_1}{w_1}\frac{P}{l^2} \quad \text{Eq. (I.7)}$$

5. Calculate the effective thickness with PCC material (Fig. I.6)
6. Calculate the required PCC overlay thickness: Calculate the required thickness D_{req} of PCC Layer using 1993 AASHTO rigid pavement design equation (Fig. I.7)
7. Calculate AC overlay thickness according to Fig. I.8
8. Carry out the statistical calculation according to Fig. I.9

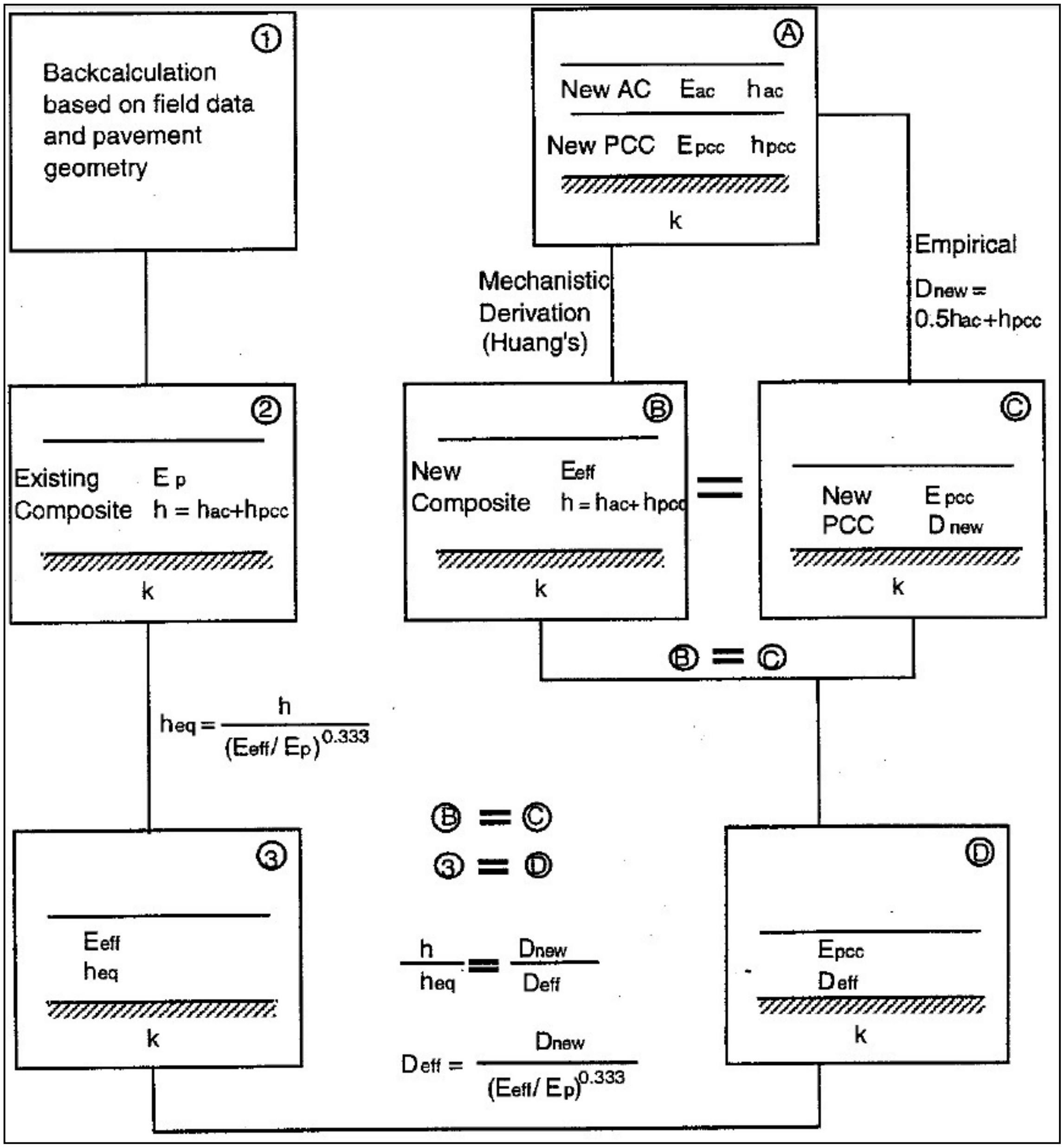


Figure I.6 Determination of effective slab thickness (Chou, 1995).

$$\log W_{18} = Z_R S_o + 7.35 \log (D+1) - 0.06 + \frac{\log\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624*10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \log \left(\frac{S_c' C_d (D^{0.75} - 1.132)}{215.63\ J\ (D^{0.75} - \frac{18.42}{(E/k)^{0.25}})} \right)$$

Figure I.71993 AASHTO rigid pavement design equation (AASHTO, 1993).

Required overlay thickness is calculated by:

$$\overline{H}_{over} = A(D_{req} - D_{eff})$$

The AC-to-PCC factor, A, is determined as:

$$A = 2.2233 + 0.0099(D_{req} - D_{eff})^2 - 0.1534(D_{req} - D_{eff})$$

Figure I.81993 AASHTO guide to calculate AC overlay thickness (Chou, 1995).

$$Design\ H_{over} = \overline{H}_{over} + Z_R s_{over}$$

$\overline{H}_{over}$ = mean value of H_{over}

s_{over} = standard deviation of H_{over}

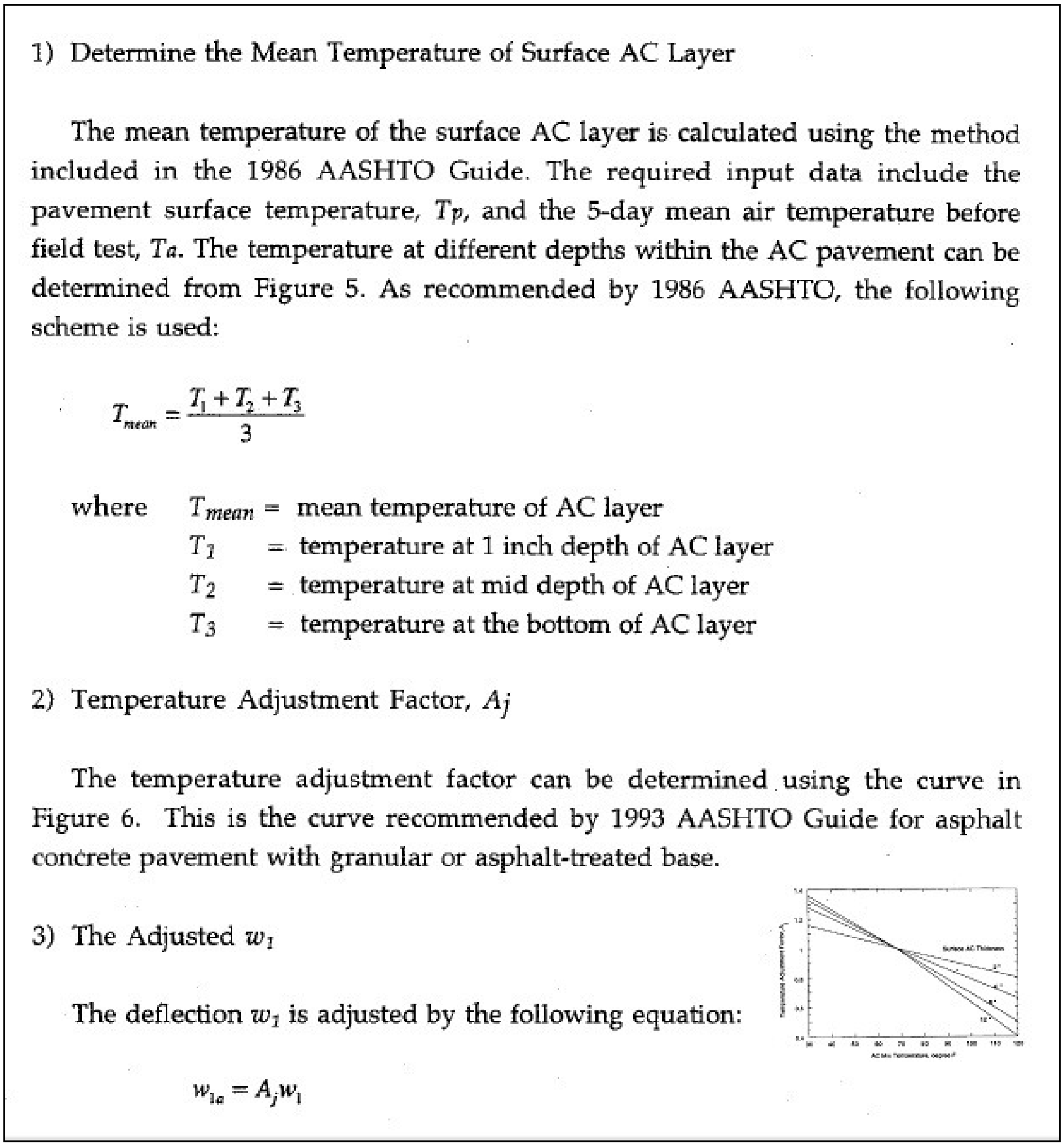
Z_R = reliability term, determined based on reliability level R

Figure I.9 Statistical calculation for overlay thickness (Chou, 1995).

I.3.2 FLEXIBLE PAVEMENT OVERLAY DESIGN PROCEDURE FOR FWD TEST SYSTEM

- Collect the deflection data and produce data file in FWD or DDX format.
- Use Eq. (I.3) to determine the subgrade resilient modulus M_R.
- By using Eq. (I.4) and applying trial-and-error method, calculate the effective modulus of pavement above subgrade E_p.
- *Determine the effective structural number SN_{eff}.*
- *Calculate the required structural number SN_{req}.*
- *Calculate the required overlay thickness.*

The procedure of Overlay Design for flexible pavement can be divided into the following steps:



1) Determine the Mean Temperature of Surface AC Layer

The mean temperature of the surface AC layer is calculated using the method included in the 1986 AASHTO Guide. The required input data include the pavement surface temperature, T_p, and the 5-day mean air temperature before field test, T_a. The temperature at different depths within the AC pavement can be determined from Figure 5. As recommended by 1986 AASHTO, the following scheme is used:

$$T_{mean} = \frac{T_1 + T_2 + T_3}{3}$$

where T_{mean} = mean temperature of AC layer
T_1 = temperature at 1 inch depth of AC layer
T_2 = temperature at mid depth of AC layer
T_3 = temperature at the bottom of AC layer

2) Temperature Adjustment Factor, Aj

The temperature adjustment factor can be determined using the curve in Figure 6. This is the curve recommended by 1993 AASHTO Guide for asphalt concrete pavement with granular or asphalt-treated base.

3) The Adjusted w_1

The deflection w_1 is adjusted by the following equation:

$$w_{1a} = A_j w_1$$

Figure I.10 Temperature adjustment in asphalt concrete (AC) pavement (Chou, 1995).

1. Collect the deflection data from FWD or DDX file
2. Carry out the temperature adjustment (Fig. I.10)
3. Determine the subgrade resilient modulus
4. Calculate the effective modulus of pavement above subgrade (Fig. I.11 and I.12)
5. Calculate the effective structural number (Fig. I.13)
6. Calculate the required structural number (Fig. I.14)
7. Determine the overlay thickness (Fig. I.15)
8. Carry out the statistical calculation

$$M_R = \frac{0.24P}{d_r r}$$

M_R = Subgrade resilient modulus, psi,

P is the load,

d_r is the normalized deflection,

r is the radial distance.

Figure I.11 Subgrade resilient modulus formulation (Chou, 1995).

$$d_0 = 1.5pa\left\{ 1 \middle/ M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2} + \left[1 - \frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}\right] \middle/ E_p \right\}$$

M_r = backcalculated subgrade resilient modulus, psi,

P = applied load, pounds,

d_0 = deflection measured at the center of the load plate *(and adjusted to a standard temperature of 20°C or 68°F)*, inches

a = NDT load plate radius, inches

D = total thickness of pavement layers above the subgrade, inches

E_p = effective modulus of all pavement layers above the subgrade, psi.

Figure I.12 Calculation of the effective modulus of pavement above subgrade (Chou, 1995).

$$SN_{eff} = 0.0045\, h \sqrt[3]{E_p}$$

h = total depth of pavement above subgrade

E_p = back calculated effective modulus of pavement

Figure I.13 Calculation of the effective structural number (Chou, 1995).

$$\log_{10} W_{18} = Z_R * S_o + 9.36 * \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left[\frac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 * \log_{10}(M_R) - 8.07$$

Figure I.14 Calculation of the required structural number (FDOT, 2008).

Determine Overlay Thickness, D_{over}

The required overlay structural number is the difference of required structural number, SN_{req}, and effective structural number of existing pavement, SN_{eff}:

$$SN_{over} = SN_{req} - SN_{eff}$$

The required overlay thickness is determined as follows:

$$D_{over} = \frac{SN_{req} - SN_{eff}}{a_{o1}}$$

where a_{o1} is the structural coefficient for the AC overlay.

Figure I.15 Overlay thickness calculation (Chou, 1995).

Figure I.16 shows the main window of the Overlay Design. The program is an add-on application in Microsoft Excel. Figure I.17 illustrates the pavement type window in which one can select the pavement type and call an FWD file from a computer drive. Figures I.18-6.20 show the input information windows for flexible, rigid, and composite pavements, respectively. After running the program, a window will show the end of the calculations (Fig. I.21). Finally, the output results can be obtained as a text file according to Fig. I.22.

Figure I.16 The main window of the Overlay Design.

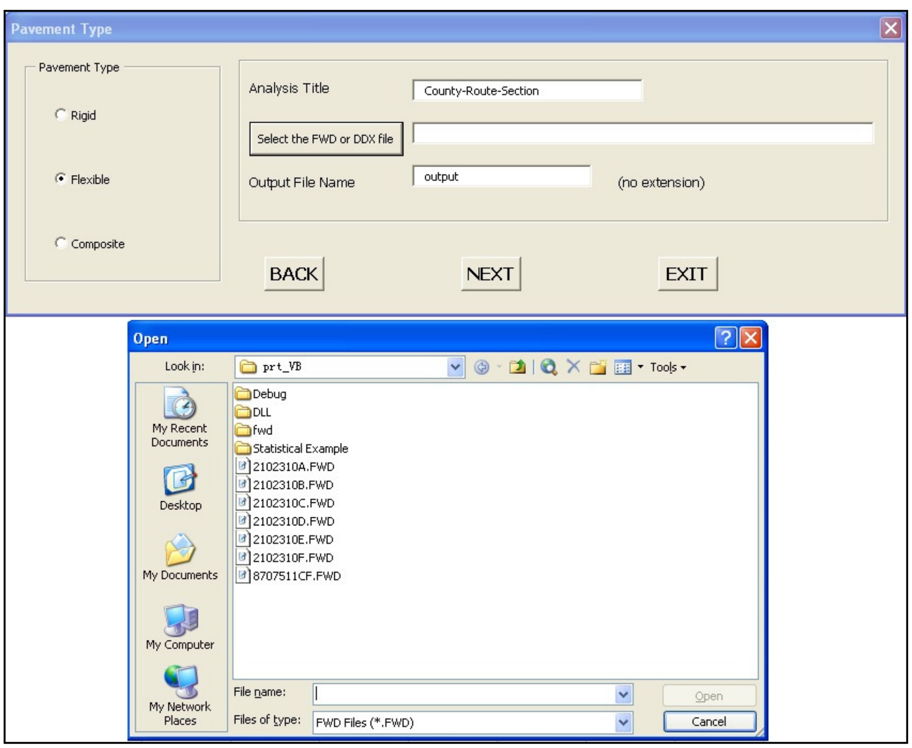


Figure I.17 Pavement type window and reading data from FWD or DDX file.

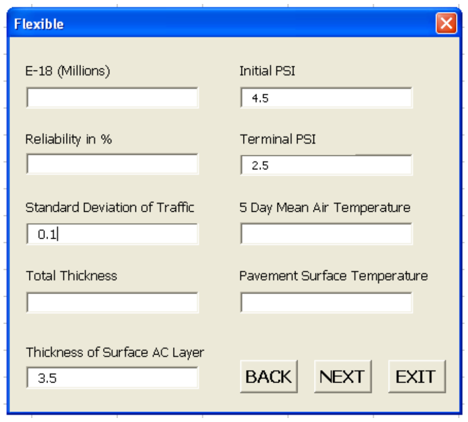


Figure I.18 Flexible pavement window in Overlay software.

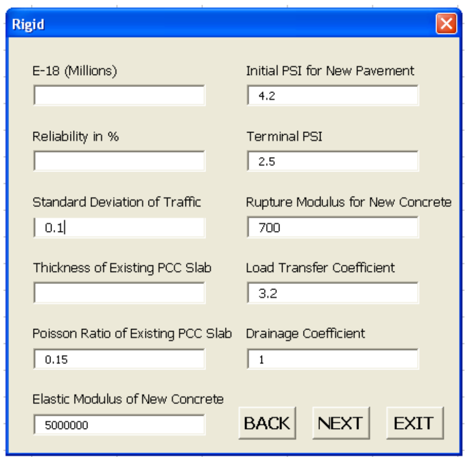


Figure I.19 Rigid pavement window in Overlay software.

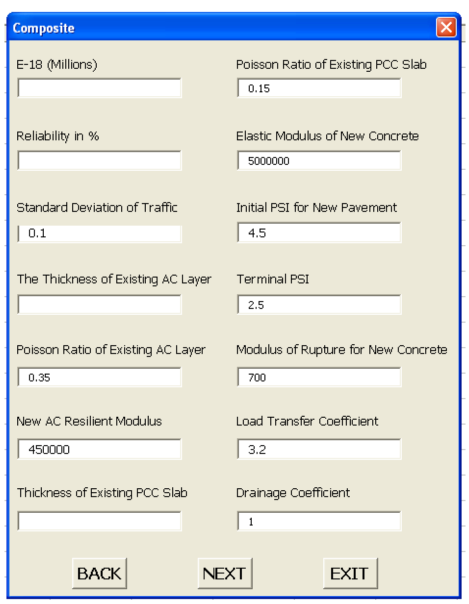


Figure I.20 Composite pavement window in Overlay software.

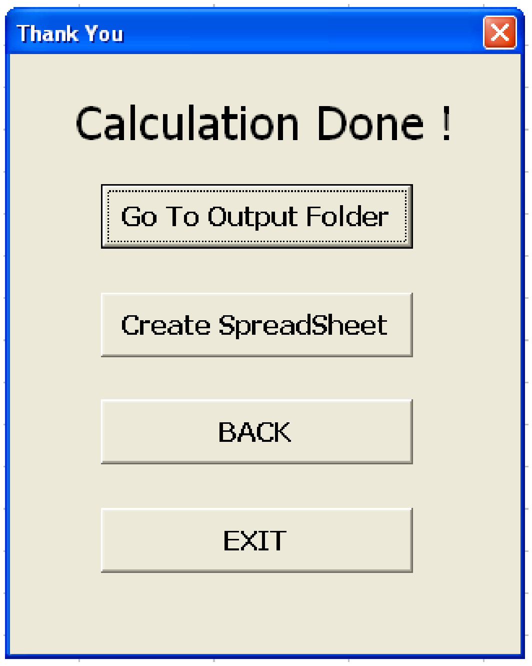
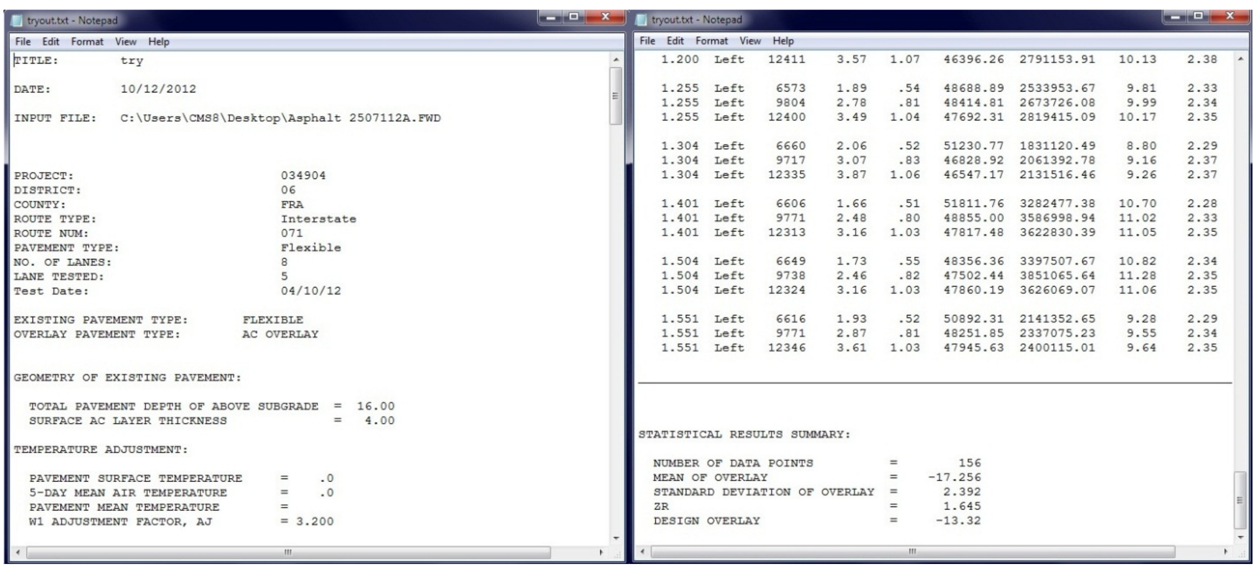


Figure I.21 End of calculation window in Overlay software.



```
TITLE:         try

DATE:          10/12/2012

INPUT FILE:    C:\Users\CMS8\Desktop\Asphalt 2507112A.FWD


PROJECT:                           034904
DISTRICT:                          06
COUNTY:                            FRA
ROUTE TYPE:                        Interstate
ROUTE NUM:                         071
PAVEMENT TYPE:                     Flexible
NO. OF LANES:                      8
LANE TESTED:                       5
Test Date:                         04/10/12

EXISTING PAVEMENT TYPE:       FLEXIBLE
OVERLAY PAVEMENT TYPE:        AC OVERLAY


GEOMETRY OF EXISTING PAVEMENT:

  TOTAL PAVEMENT DEPTH OF ABOVE SUBGRADE  =  16.00
  SURFACE AC LAYER THICKNESS              =   4.00

TEMPERATURE ADJUSTMENT:

  PAVEMENT SURFACE TEMPERATURE      =    .0
  5-DAY MEAN AIR TEMPERATURE        =    .0
  PAVEMENT MEAN TEMPERATURE         =
  W1 ADJUSTMENT FACTOR, AJ          = 3.200
```

```
   1.200  Left   12411    3.57   1.07   46396.26  2791153.91   10.13    2.38

   1.255  Left    6573    1.89    .54   48688.89  2533953.67    9.81    2.33
   1.255  Left    9804    2.78    .81   48414.81  2673726.08    9.99    2.34
   1.255  Left   12400    3.49   1.04   47692.31  2819415.09   10.17    2.35

   1.304  Left    6660    2.06    .52   51230.77  1831120.49    8.80    2.29
   1.304  Left    9717    3.07    .83   46828.92  2061392.78    9.16    2.37
   1.304  Left   12335    3.87   1.06   46547.17  2131516.46    9.26    2.37

   1.401  Left    6606    1.66    .51   51811.76  3282477.38   10.70    2.28
   1.401  Left    9771    2.48    .80   48855.00  3586998.94   11.02    2.33
   1.401  Left   12313    3.16   1.03   47817.48  3622830.39   11.05    2.35

   1.504  Left    6649    1.73    .55   48356.36  3397507.67   10.82    2.34
   1.504  Left    9738    2.46    .82   47502.44  3851065.64   11.28    2.35
   1.504  Left   12324    3.16   1.03   47860.19  3626069.07   11.06    2.35

   1.551  Left    6616    1.93    .52   50892.31  2141352.65    9.28    2.29
   1.551  Left    9771    2.87    .81   48251.85  2337075.23    9.55    2.34
   1.551  Left   12346    3.61   1.03   47945.63  2400115.01    9.64    2.35


STATISTICAL RESULTS SUMMARY:

  NUMBER OF DATA POINTS             =        156
  MEAN OF OVERLAY                   =    -17.256
  STANDARD DEVIATION OF OVERLAY     =      2.392
  ZR                                =      1.645
  DESIGN OVERLAY                    =     -13.32
```

Figure I.22 Output results in Overlay software.

I.4 VBA IMPLEMENTATION

The current VBA software is composed of the following three parts:

ThisWorkbook

“ThisWorkbook” is dealing with loading and unloading of the current software to Microsoft Excel. Therefore it includes two subroutines “Workbook_AddinInstall” and “Workbook_AddinUninstall” as shown in Appendix F.1. The instructions for installing and uninstalling the software for both Excel 2003 and Excel 2007 are also described as in Appendix F.2.

Forms

The current software comprises six UserForms which simplify the man-machine interaction operation. These UserForms basically have the same function as the DOS based man-machine interaction in the previous Fortran code of Dynaflect design. The figure of each UserForm and their background codes are listed in Appendix F.3.

Module

The software includes one Module “Module1” which is the most important part of the software. All subroutines related to the overlay design theory are included in this module. Most of the codes in this part are translated from the previous Dynaflect Fortran code except for a couple of places where theoretical modifications were made as stated above. Considering that the code structure is similar to the previous Fortran code and that the complete codes of this part are really long, the source code for the VBA was submitted on a separate disk.

APPENDIX J DATA EXPORT PROCEDURE IN LTPP

The long-term pavement performance (LTPP) program- the largest pavement study conducted so far- can be accessed by all researchers for free. It comprehensively records the experimental data of the roads distributed across North America. In this section, we introduce the step-by-step detailed operation procedure for downloading, from the LTPP website, the test data in the State of Ohio. Because the backcalculation is mainly related to the material stiffness and deflection, we will basically focus on the data export of the material profiles and FWD deflections. Other test data can be exported by a similar procedure.

Step 1

At the following website address: http://www.ltpp-products.com/, one can login to the webpage as shown in Fig. J.1. One will need to register before making use of the database.

Step 2

Using the registered email address and password to login to the account, and scrolling to the bottom of the page, and we will see the following four options (Fig. J.2):

'LTPP DataPave Online' which provides the analysis database including the data of pavement structures, pavement monitoring, traffic and climate monitoring, etc.

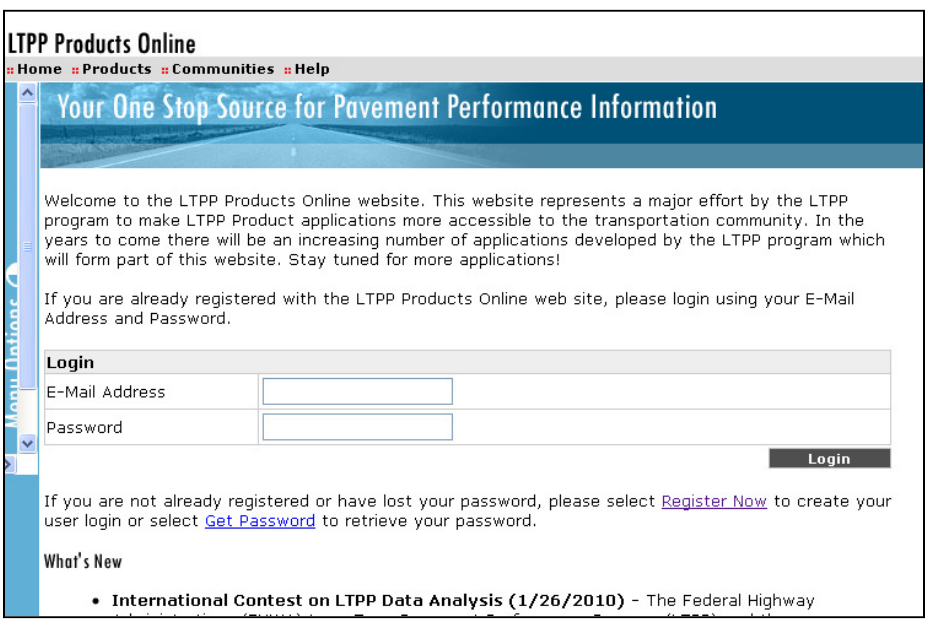
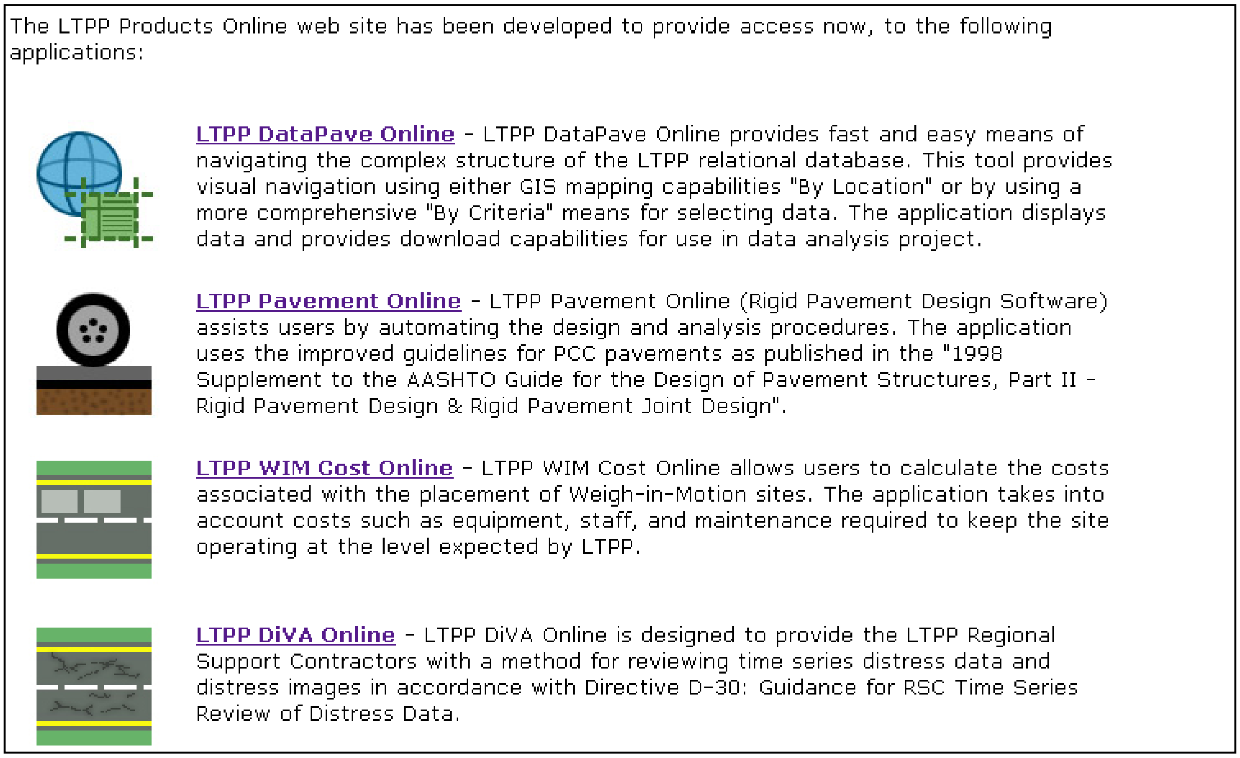


Figure J.1 Login page in LTPP Products Online.


The LTPP Products Online web site has been developed to provide access now, to the following applications:

LTPP DataPave Online - LTPP DataPave Online provides fast and easy means of navigating the complex structure of the LTPP relational database. This tool provides visual navigation using either GIS mapping capabilities "By Location" or by using a more comprehensive "By Criteria" means for selecting data. The application displays data and provides download capabilities for use in data analysis project.

LTPP Pavement Online - LTPP Pavement Online (Rigid Pavement Design Software) assists users by automating the design and analysis procedures. The application uses the improved guidelines for PCC pavements as published in the "1998 Supplement to the AASHTO Guide for the Design of Pavement Structures, Part II - Rigid Pavement Design & Rigid Pavement Joint Design".

LTPP WIM Cost Online - LTPP WIM Cost Online allows users to calculate the costs associated with the placement of Weigh-in-Motion sites. The application takes into account costs such as equipment, staff, and maintenance required to keep the site operating at the level expected by LTPP.

LTPP DiVA Online - LTPP DiVA Online is designed to provide the LTPP Regional Support Contractors with a method for reviewing time series distress data and distress images in accordance with Directive D-30: Guidance for RSC Time Series Review of Distress Data.

Figure J.2 Four database entries of the LTPP products.

'LTPP Pavement Online' which is an online assistant for automatic pavement structure design and analysis.

'LTPP WIM Cost Online' which helps users to calculate the costs for the placement of weigh-in-motion system, including costs such as equipment, staff, and maintenance.

'LTPP DIVA Online' which provides the historical data and the images of pavement distress information, and also predicts the crack trend for users.

The first option 'LTPP DataPave online' is the one used for the current research and in the following sections we concentrate on the data analysis from this entry.

Step 3

Clicking 'LTPP' DataPave Online', selecting 'Visualize' and then clicking 'Select By Criteria', the following top three dropdown boxes (Fig. J.3) include different geographical areas and states for selection will appear. Selecting OH (39) in the box 'North Central Region' and clicking 'Next', we come to another three dropdown boxes in the bottom three in Fig. J.3 including different experiment types and numbers. We select all code options in every box and then click 'Next' and click 'Next' again. This time, the main displaying page will appear as Fig. J.4.

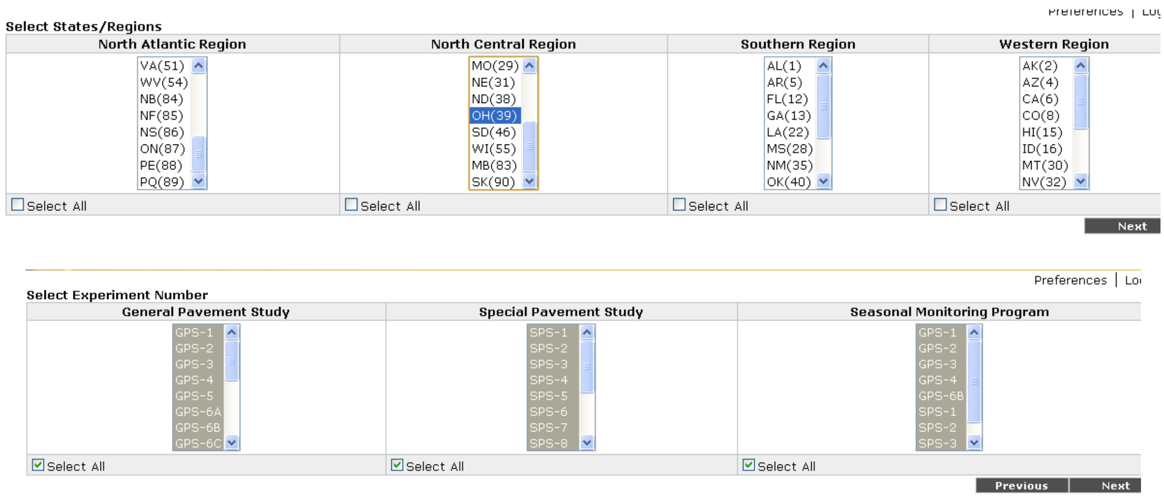


Figure J.3 Dropdown boxes in codes options.

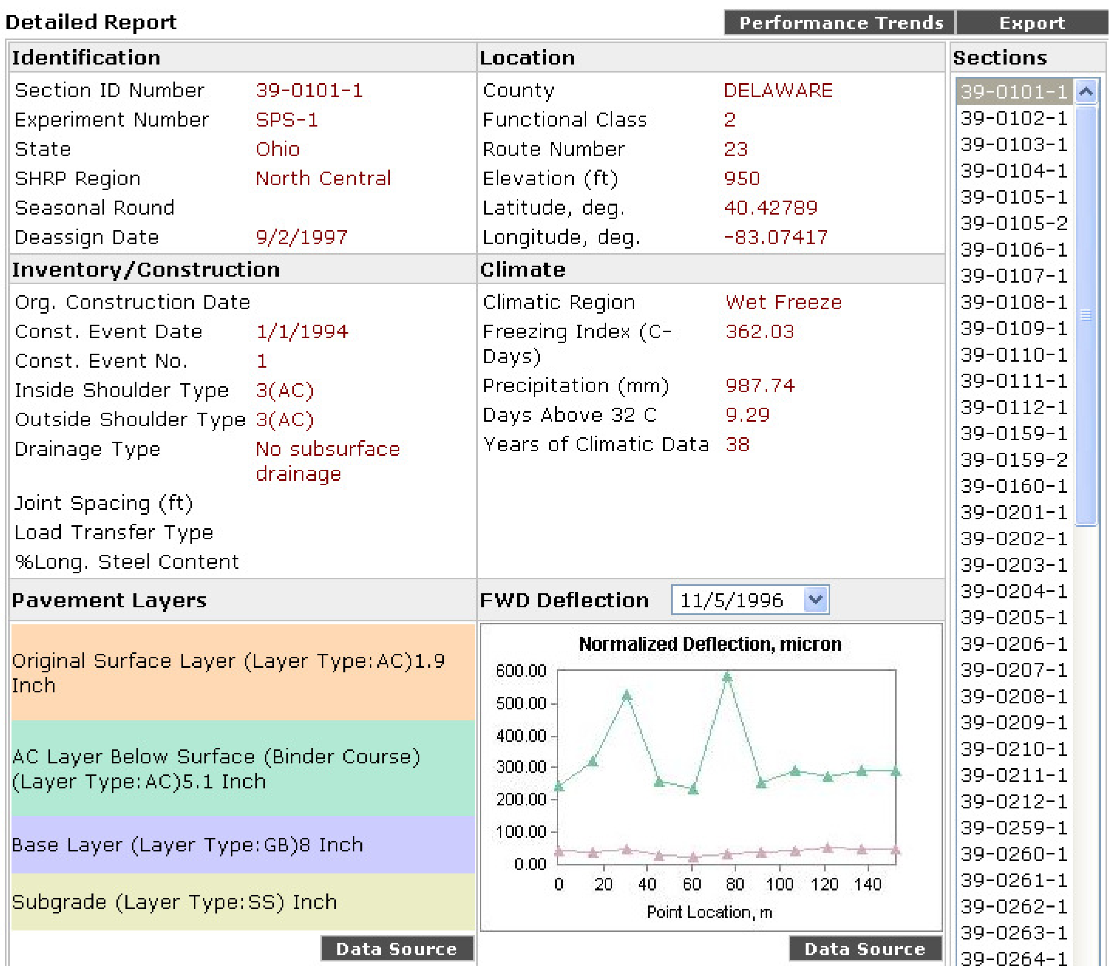


Figure J.4 LTPP data graph page.

Step 4

As shown in Fig. J.4, some important LTPP data have been selected and graphed/tabled at the center of this page which mainly includes six areas: Identification, Location, Inventory/Construction, Climate, Pavement Layers and FWD Deflection. At the right side of this page, there is the dropdown box 'Section' including the identifier numbers for all experiments that have been held in the State of Ohio. These numbers all start with 39 (refers to Ohio) since we only choose Ohio as the considered region in the last step. Generally different identifier number denotes different test location. By selecting a certain identifier number in the right 'Section' box, the values of the left areas will automatically change to the corresponding test results. Note that the values or figures shown at this page are only a small part of the whole data pool. The entire data library can be accessed when we continue proceeding to the next page by clicking 'Export' button on this page. The 'Data Extraction' page will appear as in Fig. J.5.

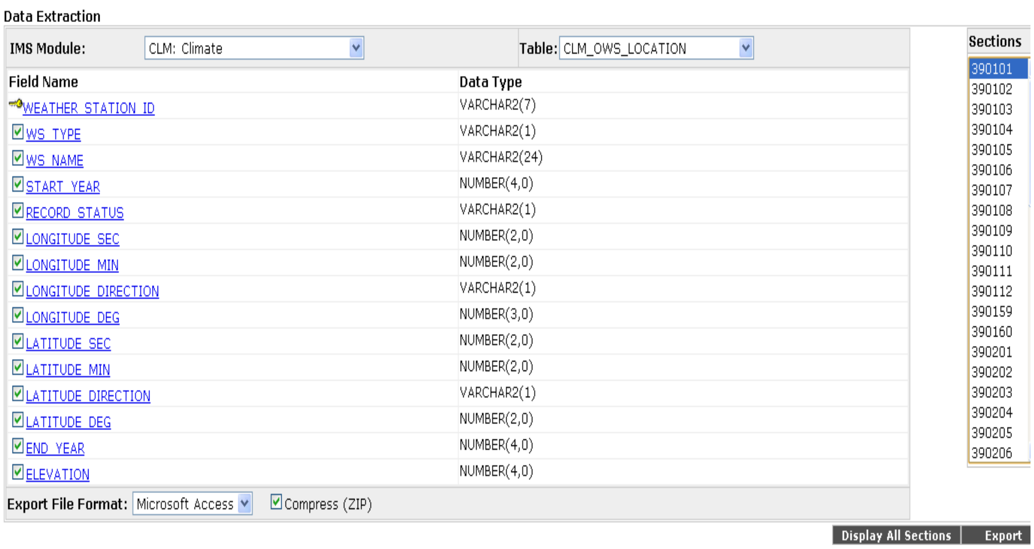


Figure J.5 LTPP data extraction page.

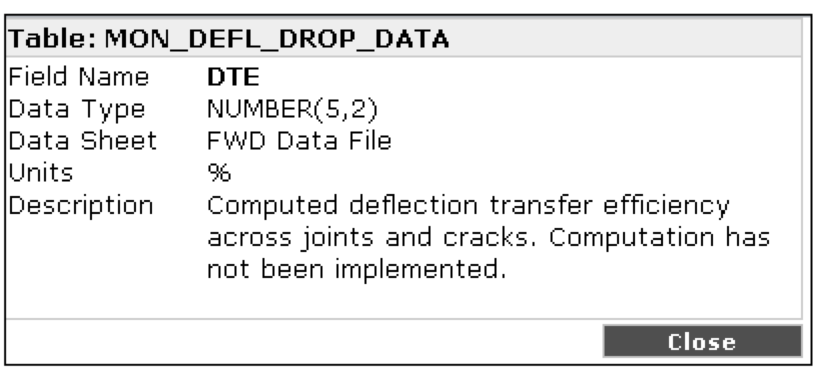


Figure J.6 The pop-up window for item 'DTE'.

Step 5

As shown in Fig. J.5, the Data Extraction page is important since the entire LTPP database including construction, monitoring, test and rehabilitation etc. of every selected road section can be accessed through this page. This page is mainly composed of two dropdown boxes: 'IMS Module' and 'Table'. IMS means Information Management System and currently include 22 data modules which are presented in Appendix A.1. For each option pair from Boxes 'IMS Module' and 'Table', a series of item names and data types appear correspondingly in the central area, respectively in column 'Field Name' and 'Data Type'. For example, if we select 'Monitoring' in the left box and 'MON_DEFL_DROP_DATA' in the right box, the updated information in the central area will include 24 items which is presented in Appendix A.2. These items and the test values will be exported in a single file. The file format can be of either Microsoft Excel or Access extension, depending on the option selected in the dropdown box 'Export File Format'. We can decide which items to be exported by checking the small box before each item. It is noted that there is a popup window for each item explaining the specific meaning when clicking the item. For example, if we click 'DTE', the popup window as shown in Fig. J.6 will appear. It is noted that before exporting the data, we need to determine the objective highway section by clicking the identifier number in the box 'Section' on the right side of this page.

Step 6

When all information has been determined, clicking 'Export' button, we will be led to the following page as shown in Fig. J.7. We click 'Download' and save the data file.

Data Export Information	
File Name:	Ruifeng-2-25-2010-12-32-5.zip
File Type:	Compressed File(ZIP)
File Size:	43.8 Kb
Table:	MON_DEFL_DROP_DATA
Fields:	TEST_DATE, STATE_CODE, SHRP_ID, DEFL_UNIT_ID, POINT_LOC, DROP_NO, TEST_TIME, LANE_NO, PEAK_DEFL_4, DROP_HEIGHT, DROP_LOAD, DTE, HISTORY_STORED, NON_DECREASING_DEFL, PEAK_DEFL_1, CONSTRUCTION_NO, PEAK_DEFL_3, PEAK_DEFL_5, PEAK_DEFL_6, PEAK_DEFL_7, PEAK_DEFL_8, PEAK_DEFL_9, RECORD_STATUS, PEAK_DEFL_2,
Sections:	39-0101

Select the Download button to download your exported data file. You can also download your exported data file at the following URL:

Download File URL: http://www.ltpp-products.com/DataPave/databases/Ruifeng-2-25-2010-12-32-5.zip

Please note that your exported data file will be deleted from the server after 4 hours. To regenerate your exported data file, select Tools -> Export History to access your data export history.

Additional Resources:
LTPP Data Disclaimer URL: http://www.ltpp-products.com/DataPave/downloads/disclaimer.pdf
LTPP Data Dictionary URL: http://www.ltpp-products.com/DataPave/downloads/ltppdd.mdb
LTPP Data Codes URL: http://www.ltpp-products.com/DataPave/downloads/codes.mdb

Back | Download

Figure J.7 Data export information on data file download page.

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