A NEW TECHNIQUE FOR THE ESTIMATION OF THE ELASTIC MODULI OF PAVEMENT LAYERS FROM LIGHT WEIGHT DEFLECTOMETER DATA

by

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Abstract

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This study developed a method to estimate the elastic moduli of a flexible pavement system from Light Weight Deflectometer deflection data. The forward method (simple equations) can be easily programmed into the data acquisition device of the Light Weight Deflectometers. The equations can be of a primary assistance in the evaluation of the flexible pavement structures. The method is simple and it eliminates the need for the backcalculation procedure after the LWD test.

The pavement systems considered in this study are composed of 2 to 4 inches of the asphalt concrete wearing layer and 4 to 8 inches of compacted granular base layer, structures commonly used for low and medium volume roads. By utilizing the layered-elastic computer model WinJULEA, surface deflections have been computed assuming various

combinations of layers thickness and layers moduli. Two different deflection datasets have been generated. The first deflection dataset was generated for three geophones offset distances: 0, 9 in and 18 inch from the center of an 8 inch diameter loading plate. The second deflection dataset was generated for the 12 inch diameter loading plate and three geophones at the offset distances of 0, 12 and 24 inches from the center of the loading plate. The subgrade moduli have been considered as a constant value (10 Ksi).

After generating the data bases, deflections have been reported in terms of two relative ratios, d_1 and d_2. The d_1 ratio is the ratio between the deflections measured by the central geophone to the deflection measured by the outer geophone. The d_2 ratio is the ratio between the deflections measured by the middle geophone and the outer geophone.

The SAS statistical analysis software was used to conduct a multi-linear regression analysis. Two sets of equations have been found best relate the elastic moduli of the upper pavement layers to the surface deflections: a pair for pavements with asphalt surface layer thickness between 2.0 and 3.0 inches and another pair for the asphalt layer thickness between 3 and 4 inches. The equations can be easily used to compute the elastic moduli of a three-layer pavement structure from the deflections measured by the LWD.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

This study presents a method for the structural evaluation of the flexible pavement layers using the Light Weight Deflectometer. Determination of the pavement effective structural capacity is important for QA/QC of the projects during the construction stages and after the project completion. But the most important estimation of a pavement structural value is for pavement management and rehabilitation process during the life time of a pavement.

Pavement structural capacity is often indicated by the Elastic Modulus of the pavement layers, E, for the bound materials (e.g. the top wearing layer and the base layer), and the resilient modulus of the subgrade soil, MR.

Several different test methods have been developed to determine the elastic modulus of pavement layers. Some test methods require coring and sampling and laboratory testing and cause damages to the pavement. Because the coring process is very time consuming and costly, these methods are not as popular. These tests are classified as “Destructive Tests”. In contrast, Non-Destructive Test (NDT) test methods are more popular and vastly used for pavement evaluation. Some of these non-destructive test devices are:

- PLT (Static Load Plate),
- Clegg Impact Tester (CIT) also known as Clegg Hammer,
- Dynamic Cone Penetrometer (DCP)
- Falling Weight Deflectometer (FWD).

The non-destructive test devices are in-situ tests that can be performed almost at any time during the construction and some of them after the construction of the pavement. Falling Weight Deflectometer is one of the most complex and yet accurate devices for this purpose. It is capable of measuring the stiffness of any pavement or soil layers at any depth. It has been used over 30 years in the United States and Europe. It is considered nowadays as a standard device in the pavement industry.

FWD is composed of a drop weight mechanism which applies an impulse load on the pavement surface thorough a circular steel plate. The load transfers into the depth of pavement layers beneath the surface. Several sensors lined up at specific offset distances from the loading plate center (the sensors distances depend on the depth of layers each sensor represents). The sensors measure the deflection at the pavement surface when the dynamic load is applied. The dynamic load of the FWD simulates the passing of a single wheel load of a truck in terms of load magnitude and load distribution area. Therefore, the moduli calculated from the FWD deflections are expected to be very similar to the moduli of

the pavement materials subjected to real traffic load. The estimation of layer moduli is normally done after the deflections are measured, using specialized software programs installed on personal computers.

Light Weight Deflectometer (LWD) is a portable and much lighter version of the Falling Weight Deflectometer (FWD). It is also much cheaper, making it a feasible candidate as a quality control device.

The objective of this study is to develop a simple method to compute the moduli of pavement layers from the deflections measured by the LWD for three-layer flexible pavement structures. Such a method must be simple enough to be incorporated in the software that collects the deflection data when the LWD is operated, such that the moduli estimation be done at the same time with the deflection measurements. This would eliminate the need for post-processing of the deflections data.

Chapter 2

Literature Review

This study presents a method for the determination of the elastic moduli of the flexible pavements layers by use of the Light Weight Deflectometer data. The Light Weight Deflectometer (LWD) is a portable version of the Falling Weight Deflectometer (FWD). The LWD testing principle is similar to those of the FWD. In this chapter, the FWD and LWD are described in details and the differences between them are discussed in order to better understand of the specifics of each device. Several deflection analysis processes are also discussed.

2.1. The Falling Weight Deflectometer (FWD)

The Falling Weight Deflectometer was originally developed in France in the 1960s, but produced at a larger scale in Denmark since 1982. Falling Weight Deflectometers have been used for more than four decades in Europe and for more than 30 years in the United States; they are considered as the standard device to evaluate the structural capacity of pavements.

Furthermore, the Falling Weight Deflectometers can be used for other purposes [NCHRP, 2008]:

- Data collection and analysis refinement,
- Pavement rehabilitation and overlay,

- Portland Cement Concrete (PCC) joint sealing evaluation,
- Pavement management systems,
- Load transfer efficiency,
- Void detection,
- Spring load restrictions,
- Non-resilient pavement layer behavior,
- Utility cuts,
- Experimental paving materials,
- Project acceptance and evaluation,
- Conversion of data from other NDT devices,
- International practices

The FWD application studied in this research is " The structural capacity evaluation" or in a specific term, " The estimation of the subgrade and pavement layers resilient moduli and elastic moduli values" (MR, E_1, E_2, ...).This would fall under Pavement Management Systems (PMS) and the Project acceptance and evaluation categories.

The FWD is used by the state Departments of Transportation (DOTs) as a device for measuring the pavement surface deflections. The deflections occur as a response to a dynamic load produced stationary, which simulates the real time passing of truck wheel load. By performing

the FWD test, the variation of the stiffness of pavement layers along a pavement section can be determined.

Some other non-destructive test methods (NDT) are used for pavement structural evaluation. Most of these tests are very popular and vastly used in the geotechnical engineering and pavement industry. In the technical literature we may find these tests referred to as RCCT (Rapid Construction Control Test devices). The RCCT devices are mostly the in-situ tests that can be performed almost at any time during the construction and some of them even after the construction.

Some of these RCCT devices are as follow:

- PLT (Static Load Plate), for measuring the soil Bearing Capacity,
- Clegg Impact Tester (CIT) also known as Clegg Hammer, measuring the compaction level of the soil fills, earth work, subgrade,
- Dynamic Cone Penetrometer (DCP), measures the subgrade density and the compaction level. There is a research focusing on the DCP test and it's correlations with the subgrade parameters, mostly the resilient modulus.

- Falling Weight Deflectometer (FWD) and the Light Weight Deflectometer (LWD), measure the pavement layers elastic modulus,

Among NDT devices, FWD is capable of producing an impulse through the ground by applying an impact loading. In these devices the impact load is applied through a bearing plate of various sizes depending on the test device capacity and the load magnitude. These devices measure a transient response load pulse (in milliseconds units). Among all these NDT devices, the FWDs (both full scale and portable models) allows the adjustment of the magnitude of the applied load. They can employ variety of loads depending on site requirement and project condition.

2.2 The Principle of the Falling Weight Deflectometer (FWD) Test

The FWD is a heavy trailer-mounted apparatus (Figure 2-1) consisting of a weight which is mechanically raised and dropped on a set of rubber buffers that transfer the impact load to a circular steel bearing plate. All these actions are controlled by an attached computer. The drop weights differ for each FWD model and it ranges between 22.05 to 1,543.24 lbs (10 to 700 kg). These weights are dropped from a height of 2 to 20 inches (50 to 510mm) (NCHRP, 2008).

The steel loading plates have diameter of 11.81 and 17.72 inches (300 and 450 mm). The uniformity of the stress distribution through and

underneath the bearing plates is guaranteed as the drop weight hits the rubber buffers first and then the impact load is transferred to the plates. The induced impact load caused by the weight mass drop is ranges about 1,500 to 53,954 lbf (7 to 240 KN) according to NCHRP, 2008. The impulse time of the applied load is varied between 25 to 40 milliseconds depending on the stiffness of the loaded pavement structure. According to the required contact pressure, the drop weight, height and the plate size can be adjusted (Petersen, 2006). After the load application, the pavement deflection is recorded through sensors known as geophones. The collected data from the field goes through a multiple analysis (discussed in detail later in chapter 3) until the pavement layer moduli can be extracted from the field data.

The benefits of using the FWD are:

- It is a non-destructive testing equipment.
- The deflection measurements are repeatable and accurate,
- The equipment is durable; many FWDs are in operation after more than 20 years of use.

Figure 2-1 Trailer Mounted Falling Weight Deflectometer

The only limitation of the FWD is that the measurements are not continuous. During the deflection measuring session, the vehicle pulling the FWD device stops at every test location to do the measurement. This required the traffic control during the test, which affects the traffic flow on the road being tested (Petersen, 2006).

2.2.1 The Components of The FWD Device

There are different types of Falling Weight Deflectometers. Trailer mounted (Figure 2-1), Vehicle mounted (Figure 2-2) and a portable, much lighter version known as Light Weight Deflectometer (LWD).

Figure 2-2 Vehicle Mounted Falling Weight Deflectometer

The components of the FWD apparatus [as stated in NCHRP, (2008)] are:

- Weight Drop mechanism: The weight drop mechanism consists of various weight drop mass that ranges between 10 to 700 Kg (22.05 to 1543.24 lbs.). In addition, there are a mechanical or a hydraulic lifting mechanism to lift the weight, and a guiding rod which helps the weight drops down onto the rubber buffers. The weight drop height can also be adjusted on the rod. The impact load caused by the drop mass ranges from about 7 to 240 KN (1500 to 53,953 lbf).
- Rubber Buffers: A set of stiff rubber buffers in shape of a cone or a half-sphere are attached either on the top of the

bearing plate or at the bottom of the weight drop apparatus. The rubber buffers guarantee the uniform distribution of the impact load through the loading plate. The number of rubber buffers used in a certain test depends on the desired impulse duration time. In some models a set of springs is used instead of the rubber buffers.

- Loading Plates (Bearing Plates): A circular steel plate which provides a suitable contact with the material underneath insures a uniform load distribution over the pavement surface. The loading plates are constructed to allow the measurement of the deflection at the center of the plate. As the dropping weight hits the plate, the resulting force is applied perpendicular to the surface being tested.
- Load cell: It is a sensor that measures the magnitude of the applied load to the loading plate. The load cell is placed as close as possible to the loading plate in a way that it does not cause any interruption in obtaining deflection measurements under the center of the load plate. Load cells are resistant to the different testing environments and conditions such as wet surfaces or mechanical shocks

caused by the impact load or the travelling to the testing spots.

- Geophones: Geophones or deflection sensors convert the dynamic deflection caused by the impulse load into the electrical voltage. In other terms the Geophones translate the vibration information into an analog electrical signals based on magnetic induction principles. The geophones are attached to a beam placed radially from the loading plate. Different spacing for the geophones can be used depending on the number of sensors being used and the pavement surface condition. The most commonly used spacing configuration are listed as follow: (-12,0,8,12,18,24,36,48,60 in) for a nine-sensor FWD, and (0,8,12,18,24,36,60 in) for seven-sensor FWD on a flexible pavement. For seven-sensor FWD on a rigid pavement, the following spacing is the most commonly used: -12,0,12,18,24,36,60 inches.

When the specialized impact load hits the bearing plate it transmits the load to the load plate, which causes the deformation of the pavement surface in the shape of a bowl, popularly called deflection bowl. (Figure 2-3). The recorded deflections are from the peak measurements of at least

six geophones placed at radial offset distance from the center geophone which is positioned at the center of the loading plate.

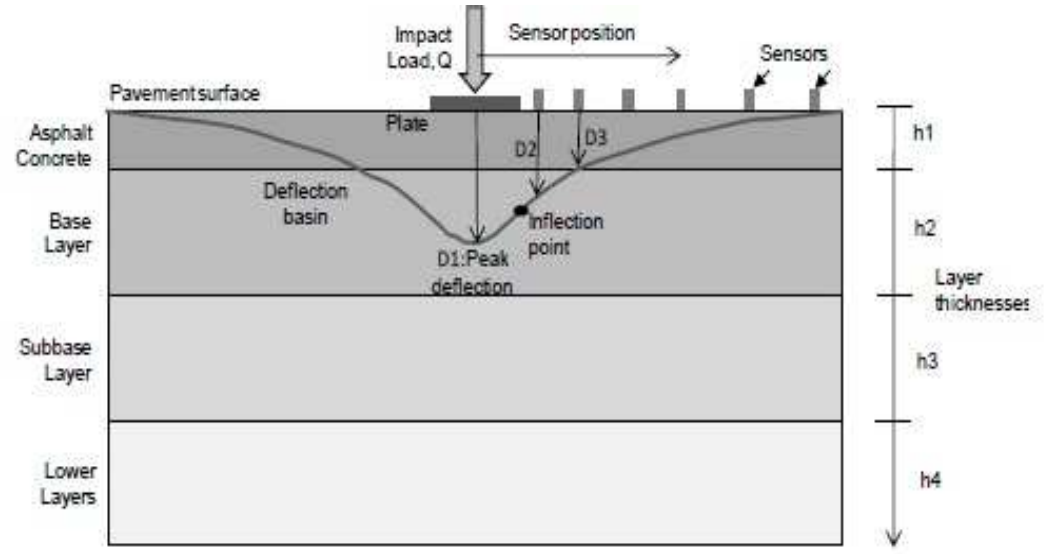

Figure 2-3 Deflection Bowl Profile and The Geophones Arrangement

2.3 Light Weight Deflectometer (LWD)

The Light Weight Deflectometer (LWD) is a scaled down, lighter and portable version of the Falling Weight Deflectometer (Figure 2-4). Originally developed in Germany in 1980s, LWD is an equipment that can determine the modulus of the layer underneath. The most common use of LWD is assessment of the in-situ elastic modulus of the compacted soil. Although the research studies on the LWD are relatively limited it has been shown that the LWD has the potential to replace many other test such as California Bearing Ratio (CBR), Plate Load Test (PLT), and Field

Dry Density (FDD) that measure the stiffness of the compacted soil but are more difficult to perform.

Figure 2-4 Light Weight Deflectometer With a Single Geophone

Furthermore the LWD is increasingly being used as a non-destructive evaluation tool in the in quality control and quality assurance process for earth work construction.

2.3.1 LWD Test Principles

LWD test is similar in principle to Plate Load Test (PLT), but it applies an impact load, not a static load. The technology used in LWD development is similar to the one used in FWDs. The important difference

between the LWD and FWD is that the LWD induces a smaller impact load and shorter load pulse duration in comparison with the FWD, due to the lighter drop mass. The drop mass of the LWD can be lifted by just one person (Fleming et. al 2007).

As the FWD, LWD can also simulate the loading of a moving single wheel. The load magnitude, plate size and dropping height can be adjusted to adapt to different test conditions. The LWD induces a non-destructive shock wave (impulse) into the soil or on the surface of the pavement when an impact load of falling mass hits the loading plate. The magnitude of the falling mass could be 22, 33, 44 lbs. (10, 15, 20 Kg). The falling mass (drop weight) could be dropped from various heights ranging from 0.4 to 33.5 inches (10 to 850 mm). The loading plate transmits the impact force to the underlying surface. The diameter of the loading plate could be 6, 7.88, and 12 inches (100, 200, 300 mm). Similar to the FWD, LWD also has a rubber buffer system which distributes the load uniformity to the loading plate and through the layers underneath. The rubber buffers (or some models have stiff metal springs instead of rubber buffers), mostly cone shaped and removable. The number of rubber buffers can be changed depending on the desired impulse duration. More buffers make the system stiffer and reduce the pulse duration.

The response of the produced impulse is recorded by one geophone at the center of the loading plate. In most models of the LWD, there is only one geophone at the center. Therefore the only material parameter that can be measured from the collected data is the elastic modulus of a single layer. When used on a layered structure, the LWD can only estimate the composite modulus of all materials underneath, which is sometimes referred to as the total stiffness of the pavement section (Fleming et al., 2007).

Some LWD models such as PRIMA100 (the model used in this study), have two additional geophones that can be place at radial offset distance just like the deflection sensors in the FWD (Figure 2-5). With the collected data from 3 geophones, the stiffness of maximum three layers can be estimated as the deflection recorded by each geophone reflects the stiffness of a certain layer within the pavement. Very few studies used more than one geophone because, for routine testing, it is more cumbersome to move the equipment around the site when equipped with three geophones. In most cases, two technicians are needed for this purpose.

Figure 2-5 PRIMA100 With Two Additional Geophones

2.3.2 Principle of The LWD Testing

There are several different models of LWD devices on the market; most of them are manufactured in Europe. The analysis focuses on studying only the peak values of the force and vertical displacement time history. By means of this method which has a dynamic nature, the static properties of materials can be derived (the peak value method is a dynamic approach of time history interpretation, by means of time history curves the static parameters are calculated such as elastic modulus of

material). The impact of a free-falling mass (the drop weight or mass slides down a guiding rod on its own weight, 10 & 20 Kg) induces a non-destructive wave (impulse or shock wave) with the duration of 15-20 milliseconds on to the soil or pavement. The generated impulse load ranges from 1 to 15 KN (with the 10 Kg drop mass, the induced impulse load is 7 to 10 KN, Grasmick, 2013). The contact pressures result from the drop mass of 10 Kg (the impulse load of about 7 to 10 KN) can range about 100-200 KPa (14.5-29 Psi) [Fleming et al., 2000]. The LWD can apply to the subgrade soil a stress similar to the stress generated by the load of the truck traffic at highway speed. When a 10 Kg mass falls on the 30 cm (12 in) diameter bearing plate, it generates a contact stress of 100 KPa on the subgrade soil (single layer) and when applying on the 20cm (7.88 in) bearing plate on a base layer the contact stress will be 200 KPa [Grasmick, 2013]. This range of stress is similar to the stresses generated by a 9,000 lbs. wheel load to a subgrade and base layer.

The diameter of the plate influence the amount of pressure transferred to the layers. The pressure reduces as it is distributed from top down through the pavement layers. Ayyanchira, 2014, has studied the applicability of different sizes of the LWD load plates on the materials based on their stiffness. The particular LWD device Ayyanchira used in his study has two bearing plates of 140mm and 200mm diameter. The author

has suggested that the 140mm plate should be used when the soil underneath has a stiffness (Young's modulus) of 10 to 1,200 MPa, and that the 200mm diameter plate should be used for soils with the Young's modulus less than 10 MPa. When the measured deflection is more than 5mm while using the 140mm plate, the 140mm plate should be replaced by the 200mm plate [Ayyanchira, 2014].

When the drop mass hits the rubber buffers and the force is transmitted to the bearing plate, the impact force is measured by a load cell installed at the center of the loading plate. The material's response under the known impact load is measured by the geophone. The process of calculation of the deflection and the layer modulus is being done by means of software embedded in the hand-held processor attached to the load cell and the accelerometer. The Young's modulus of the material is determined by the software as well as other parameters such as the impulse duration, deflection information, the rebound deflection and the applied load. The Boussinesq formula is used for this purpose.

In LWD models with more than one geophone, all parameters mentioned above are calculated from the deflections measured by each geophone separately. The parameters determined by the software are displayed instantly on the screen after every drop. The Boussinesq formula is also used for this purpose

Using lower level of impact load, LWDs are more popular to be used on unbound materials such as soil, and granular layers. These materials are relatively soft and therefore they require the lower impact loads. The use of LWDs on cemented materials such as asphalt concrete is limited but the ASTM International has developed a standard test protocol for deflection response measurement of soil, granular rock beds and even the asphalt layers [FHWA case study blog, Mike Morvak].

2.3.3 Factors Influencing The LWD Results

There are many known factors that affect the surface stiffness determined by LWDs. The drop weight, falling height, buffers (the number of rubber buffer can affect the impulse duration), bearing plate size (magnitude and depth of stressing), temperature and proper contact between the loading plate and the surface of being tested (Posribink et al., 2012, Fleming et al., 2009, and Mooney & Miller, 2008).

Posribink (et al., 2012) have studied the influence of the load plate diameter and the falling height on the determination the surface stiffness. In the research, other contributing factors that could have an effect on the surface stiffness have been kept the same. It has been observed that the falling height has no significant effect on determining the surface stiffness values. Posribink has mentioned similar studies (Lin et al., 2006, Kim et al., 2007, Kaussi et al., 2010), that have also indicated that the falling

height has no dominant effect. Furthermore, the size of the loading plate is more significant since the surface stiffness determined from the 100mm diameter bearing plate is nearly 1.5 times more than the stiffness determine when the plate with 200mm diameter is used [Posribink et al. 2012, Fleming et al., 2009].

Another factor that has an important contribution in the accuracy of the measurement is the proper contact between the loading plate and the pavement surface. Fleming (et al., 2007) has declared that the proper surface contact between the bearing plate and the pavement (any surface being tested) can significantly bias the deflection measurement and the stiffness modulus of the layer. He also mentioned that the ill-reported deflection data can be detected by studying the time history of the loading.

The loading plate diameter is one of the factors that change the LWD's test condition. The plate size is changed to achieve the desired contact stress. For instance, a 10Kg drop weight and the 300mm diameter plate can generate the contact stress of 100KPa on subgrade and sub-base which is a simulation of a passing truck at highway speed. If using the 200mm plate under same test condition, the induced stress will be 200KPa and the influence depth is only within the base layer. Of course the depth of influence is a very important factor here, because the loading dissipation through the wearing layer of the pavement is very important

and can affect the amount of the stress transferred to the layers underneath. Moreover, it has been reported (Fleming et al., 2000, Nazzal et al, 2007, Adam et al., 2009, Mooney & Miller, 2009) that right under the center of the plate, the influence depth of impact load is about 1 to 1.5 times the diameter of the plate [Grasmick, 2013].

The LWDs with a single sensor can only be used to estimate elastic modulus of the layer at the maximum depth of 1 to 1.5 times the plate diameter. If the layer being tested is composed of a uniform and homogeneous material, like a compacted soil or subgrade, the reported modulus is indeed the true modulus of that material. But if the LWD is used on a layered structure like an asphalt pavement, the interpretation of the layers modulus become more difficult. The problem that occurs here is that when using a single geophone LWD for a test, the modulus reported for the target influence depth is usually the composite moduli of the materials appear to be within that depth and the true modulus cannot be determined. In these cases the use of additional geophones benefits the derivation of the layers modulus within the desired depth. The maximum number of geophones used in LWD devices is three, and they should be placed at the studied radial offset distance.

Only a few studies have investigated the effect of the radial offset geophones. Horak (et al., 2008) performed a pilot correlation study of the

FWD and LWD deflection in an experimental construction site consisting of an emulsion treated sand layer over a compacted sand sub-base and subgrade. The results from the LWD and FWD test have been supported by studying the correlation between other in-situ evaluation test devices as well. He found that the deflections recorded from the LWD radial offset geophones (at 30mm and 60mm from the center, or 12 and 24 inches from the center) have much stronger correlation with the FWD deflections measured at same spacing than the deflection recorded from the center geophone. He also concluded that this difference is because of the shallower depth of influence of LWD, due to the lighter drop mass and the shorter drop height in LWD test. Horak has suggested that the correlation between the deflection bowl parameters of LWD and FWD are material specific. Therefore for the accuracy of the LWD test, more information of the materials such as density and moisture content should be collected by other non- destructive test (nuclear gauge) if there is no FWD test to be compared with.

In another study, Ahmed and Khalid (2011) used a LWD with a 7.88 inches (200mm) loading plate and 2 additional geophones placed at radial offset distance of 200mm and 400mm from the center of the plate. The tests have been performed on a fabricated soil box consisted of 2-layer constructions of different mixes of limestone and incinerator bottom ash

(IBM). They have produced a three-dimensional finite element model with the same loading condition as the LWD test that they were performing. The deflection results of the FE model have been compared with the measured deflections of the LWD test. The primary assumption of the layers modulus was the moduli calculated with the Boussinesq's equation (suggested by the LWD manufacturer). After the backcalculation process, the measured deflections have been matched up with the FE model, then the layers moduli were derived. The authors concluded that the modulus calculated from the FE model is a bit higher than the modulus calculated by the Boussinesq's equation.

In another study, Mooney and Senseny (et al., 2010) have performed the LWD test on a stiff over soft 2-layered soil, using the 300mm bearing plate and the radial spaced geophone at 750mm from the center. They have come to a conclusion that the layers modulus backcalculated from the deflection recorded at 30 inches (750mm) distance matches the layers modulus derived from the laboratory test. The authors have also found that the influence depth of the LWD can be up to 1.8 times the plate diameter.

Steinert (et al., 2005) performed a LWD test with 3 geophones on an asphalt layered pavement to evaluating the pavement support moduli during the spring thaw. Seven different asphalt pavement sites have been

tested by LWD and other supporting test apparatus to monitor the temperature, layers moduli changes, moisture and other parameters that contribute to the weight restriction according to the spring thaw. The results have been compared to the conventional FWD test results and it has been observed that, with the specific radial spacing, drop height and the drop mass that have been used for the LWD test on monitored sites, the only reliable correlation between the LWD and FWD was the composite modulus backcalculated from the central geophones. The authors have declared that the deflections recorded by additional geophones at the radial spacing (0, 8, and 16 in) cannot be used in the existing backcalculating software for the individual layer moduli. The modulus reported for each layer based on the reading from additional geophones is about the same as the composite moduli calculated for the asphalt layer underneath the center.

In a recent study, Grasmick (2013) has investigated the accuracy of the radial offset geophones on prediction of the sub-layers modulus using a simplified version of the Boussinesq's equation for surface deflection of an elastic half-space. The pavement was assumed to be a two-layered system consisting of one subgrade with infinite depth and a pavement layer (wearing coarse, base, sub-base) above the subgrade with the equivalent thickness D and the effective modulus of E_p. The subgrade

modulus can easily be backcalculated form the simplified Boussinesq's equation employing the radial offset geophones data.

Grasmick has studied the effect of LWD test with 2 additional geophones on a 2 set of 2-layered box system. One consisted of soft layer over a stiff layer and the other was stiff layer over a soft layer. The experiment was not as desired; the main problem was that the wooden box and the concrete floor underneath the box interfered with the peak deflection. But even then some reasonable correlation between the deflection data recorded from the LWD central geophones and the numerical Finite Element model was found. Following his laboratory experiment, he performed seven different field tests which indicated that the composite modulus derived from the central geophone in LWD is correlated with the composite modulus estimated from the FWD test as follows: $E_{LWD} = 1.8\ E_{FWD}$. He has also found that the value of the composite modulus from the central geophone is highly dependent upon the subgrade resilient modulus. Therefor there is an absolute need to evaluate the subgrade modulus as close as possible. For a more accurate evaluation of the subgrade resilient modulus, the radially offset geophones must be used. The deflection bowl parameters recorded from the radial offset geophones during Grasmick's field test have shown relatively good correlation with those of the FWD test; the correlations were even stronger

than that for the central geophone. Grasmick has found that the LWD is a reliable and repeatable test that can be successfully used for quality control and quality assurance of the projects even on day to day bases. He recommends that more research should be done debating the LWD and the radial offset geophones to raise the acceptance of this device in more specifications and developing its application in a routine base.

2.4 The Correlation Between The FWD and LWD

The FWD has been considered as one of the most accurate in-situ test devices used for pavement structural evaluation. Therefore it is regarded as a reference method to evaluate the pavement layers moduli. The ASSHTO Design Guide (1986-1993) suggests that the backcalculated modulus from the FWD test on subgrade materials are 2 to 3 times higher than modulus measured in the tri-axial test conducted in the lab [Ping et al., 2002, Horak et al., 2008].

Other researchers have directed studies investigating the correlation between different non-destructive RCCD (Rapid Construction Control Devices). The devices were Clegg Impact Tester (CIT) also known as Clegg Hammer, the Dynamic Cone Penetrometer (DCP) and the Static Plate Load Test (PLT), (Thomson et al., 2008, Horak et al., 2008). These

non-destructive devices have been considered as most vastly applied in field test.

It should be taken under consideration that the correlation studies are not always in terms of the modulus calculated for the construction layer. The FWD and LWD are devices and can be used in different test conditions. For instance, they can be used on single layer construction, multi-layered pavement structure, soft or stiff materials, using one or multiple geophones. Studies focusing on these different patterns of LWD device are as follow:

1) In some cases the LWD has been tested on single layer construction (compacted subgrade) on site or on a single layer compacted material in a wooden box in the lab. The final LWD results in such criteria can be compared with subgrade modulus backcalculated from the FWD test or measured in the triaxial test in the lab.
2) Another testing pattern is that when using the LWD on a layered system using only the center deflection sensor. In that case the modulus calculated form the readings is a composite modulus of the combined layers. Although the results may be ambiguous for an individual layer, but the overall stiffness of the layers underneath can be estimated.

The final modulus obtained from this test is the composite modulus of the pavement.

3) The most complicated LWD test criteria are when additional deflection sensors (geophones) on redial offset distances are being used. There are only a few researches in which the authors have investigated the applicability of the radial offset deflection sensors.

Fleming (et al., 2000) has performed field test using three LWD devices: PRIMA100, TRL Foundation Tester (TFT), and the German Dynamic Plate Bearing Test (GDP). He compared the resilient modulus calculated based on the LWD results with that derived from FWD. He introduced a correlation coefficient for test and device. He concluded that the correlation coefficients are instrument specific. Therefore it is a necessity to first establish the correlation coefficient for the FWD before performing any test with LWD.

Horak (et al., 2008) directed the LWD and FWD correlation test. The correlations found between the peak deflection of 300mm offset geophone and the 600mm offset geophone were rated by the regression R-square of 0.82 and 0.67 respectively and the R-square reported for the central geophone was even worse than the other sensors.

Horak and Khumalo (2006) have conducted a pilot study of the LWD and FWD correlation focused on the possible use of the deflection bowl parameters from LWD tests in a similar fashion to that used and developed for the FWD. Calculation of the surface modulus is standard output generated by both FWD and LWD. The moduli values determined from FWD and LWD test results were correlated so as the correspondence deflection bowl parameters of both LWD and FWD.

Rahimzadeh (2004) also declared that the correlation results of LWD and FWD are dependent on the layer thicknesses. Nayyar (2012) reported that the LWD modulus is about 3 to 4 times the modulus calculated by FWD. She has also find that the elastic modulus from the LWD test is about 3 to 4 times higher than the modulus retrieved from a laboratory triaxial test. And yet the FWD modulus is about 1.65 times the laboratory resilient modulus.

Shafiee (et al., 2007) studied the FWD and LWD test performance in evaluating the subgrade modulus. The subgrade modulus calculated from the FWD was found to be 1.16 times higher than the modulus calculated from the LWD test. He found that the correlation factor can be closer to 1.0 if the FWD and LWD are designed for the same loading and stress condition.

Petersen (2007) studied the possibility of predicting the subgrade modulus from the LWD deflection measured during the in-situ testing at project sites. Along with the LWD test, the moisture contents and density of the same spot have been measured. Soil samples from the same spot have been taken as well and were tested in the laboratory. Petersen was able to produce correlations between the lab test results and in-situ data. He developed a regression model between the in-situ LWD deflection data and the laboratory determined triaxial resilient modulus of the soil compacted at the in-situ dry density and moisture content. The study showed that there is very good correlation between the LWD test results and the subgrade stiffness derived from the laboratory tests. Furthermore, the resilient modulus calculated from LWD has been compared to those from FWD backcalculation in a few testing site. The correlation between the calculated modulus from both LWD and FWD was found satisfactory with R-square value of 0.836.

Steinert (et al., 2005) studied different pavement constructions such as subgrade, sub-base and even the asphalt layered pavement. The interesting aspect of this work is that he found that there is a very promising correlation of (E_{LWD}=1.33E_{FWD}) between the LWD and FWD reported modulus when testing thinner asphalt layers with thickness of 5 to 7 inches. This study is among the few which has investigated the LWD

modulus correlation on a layered system. Correlation factors reported by researchers are included in Table 2-1.

Table 2-1 E_{LWD} and E_{FWD} Correlation Factors

Steinert (et al., 2005)	E_{LWD} =1.33 E_{FWD} (E_{FWD} =0.75 E_{LWD})
K.P. George (2006)	E_{FWD} =1.09 E_{LWD}
Fleming and Frost (2000)	E_{FWD} =1.03 E_{LWD}
Nazzal (2003)	E_{FWD} =0.97 E_{LWD}
Philips (2005)	E_{FWD} =1.23 E_{LWD}

2.5 The Use of Light Weight Deflectometer for Quality Assurance and Quality Control

The adoption of LWD as a QA/QC device has grown rapidly in Unites States. The QA/QC aspects of LWD have been investigated by few researchers. They all concluded that for a thorough evaluation of a construction (quality assurance or quality control) additional in-situ test devices shall be used in parallel with the LWD. One of the vast implications of the QA/QC is the construction of the subgrade modulus. Hossain (et al., 2010) prepared a report inspecting the LWD in QA/QC application. He reported that the common and most used ways in subgrade qualification is the dry unit weight measurement with the Nuclear Density Gauge (NDG) or the Sand Cone Test (SCT), because there is no

tangible yet more accessible field measurement to do so. He also mentioned that application of the LWD in QA/QC aspects can be reached if only a good understanding of the device operation, test variable and data quality obtained. The main target of using LWD in QA/QC field is predicting the FWD moduli from the LWD data. Several researchers (i.e. Nazzal 2003) have developed prediction models for their own particular cases but there is no universal model as of now.

Although the LWD device has been employed in many QA/QC studies by several researches (Nazzal 2003, Petersen 2007, Steinert 2005, etc.) in United States in past few years, Shabir Hossain suggested that LWD test shall be used along with moisture-density test devices for subgrade compaction evaluation (when there is a need to know the modulus). But whenever the LWD is being used only to investigate the uniformity of the construction as a QA/QC tool, the LWD can be used without moisture content and density collection.

In another study Mooney (et al., 2008) reported that when using the LWD for QA of mechanically stabilized earth wall (MSE) and the bridge approach earthwork, LWD has showed higher variability than the Clegg Hammer and the Dynamic Cone Penetrometer (DCP).

Another aspect of the LWD QA/QC has been addressed by Steinert (et al., 2008). In his research, he concluded that LWD can be

applied as a QA/QC tool to evaluate the strength loss experienced by specific roadways during the spring thaw so the load restrictions can be applied or removed. He recommends that the complex modulus of the particular roadway prone to the load restriction can give enough information of the frost depth and pavement layers condition when comparing to the unfrozen condition of the same roadway during the monitoring season.

Chapter 3

Deflection Data Analysis With FWD and LWD

3.1 Introduction

The most accurate and efficient way to perform the structural evaluation of pavements is with the Falling Weight Deflectometers. The most important parameter derived from the FWD test is the layers moduli which can be used in the pavement design, rehabilitation practices, and the estimation of the remaining life of the pavement. Derivation of the modulus from the FWD or LWD field data is difficult and requires good engineering judgments. Two major concepts will be discussed in the following chapter, backcalculation and forward calculation. These concepts are vital to the data interpretation of the FWD/LWD devices and layers moduli derivation. As discussed in Chapter One, the main target of this study is to developed a method that uses LWD deflection data in the same fashion as the FWD data is used in the backcalculation procedure. Therefore, it is useful to review the derivation of layers moduli from the FWD deflection data. This may assist in the development of an approach which uses the LWD deflection basin data for layer moduli derivation.

There are some technical terms that need to be defined first:

1) *Pavement Composite Modulus*: Some in-situ test apparatus or test procedures may report the stiffness modulus representing all layers

of the pavement structure above the subgrade; this overall modulus is known as the composite modulus.

2) *Deflection Basin/Bowl*: When performing a FWD test on a surface (subgrade surface or pavement surface), the pavement deflects when the load is dropped (Figure 3-1). An area of almost 3 to 7 feet away from the loading point is affected. The deflection caused by the load is extended in shape of a bowl, called the deflection bowl. The size and shape of the deflection bowl may vary according to the load magnitude, pavement layer composition, layer stiffness, loading plate size, load impulse and duration, temperature, and etc. Because the deflection bowl parameters are highly correlated to the pavement structural strength and characteristics, the more accurate the deflection bowl parameters are measured the more accurately the layers moduli can be derived from the FWD test. The number of deflection basin parameters measured from a FWD test depends upon the number of the deflection sensors. Normally, up to nine geophones can be used in a FWD test. Of course the magnitude of the load influence the depth and the extent of a deflection basin. For this reason, smaller and lighter devices, such as the Light Weight Deflectometer (LWD), cause a smaller bowl than that made

by the FWD. Also the LWDs can only be used more effectively for shallower layers (Horak and Khumalo, 2006).

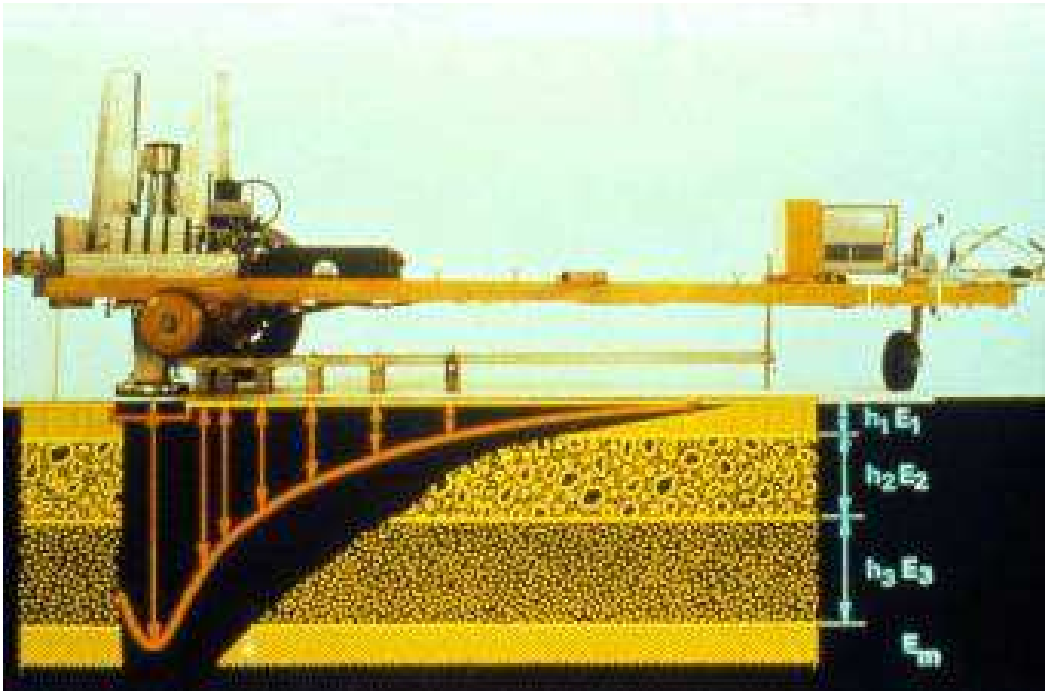

Figure 3-1 Deflection Bowl, and Pavement Profile Under FWD Test

3.2 Moduli Backcalculation

Elastic moduli of the pavement layers can be derived from the deflection basin created by applying a load to the pavement surface with the NDT device, using backcalculation and some other techniques.

Backcalculation can be defined as an iterative process by means of which the pavement layer moduli can be estimated from the FWD deflection data [NCHRP, 2008]. Backcalculation of the FWD data provides quick and reliable information about the in-situ stiffness of the individual

layers (Das, 1994). The process computes deflection values with the same geophone configuration that is used in the FWD test at the site based on an assumed elastic moduli values and Poisson's ratios of each layers.

Then the deflections of the pavement model are compared with the measured deflection values from the FWD test, using an iterative mathematical model. The layer moduli that have been assumed are adjusted after each iteration until the measured and calculated deflections (from the FWD test) match within a level of tolerance. The last set of layer moduli are the backcalculated moduli of the pavement layers.

"Backcalculation procedure is more of an art than a science" termed by Stubstad (et al., 2005). It is scientific and meticulous because the entire deflection basin can be accurately used to match the theoretical and measured deflections and find the backcalculated moduli. However, there are some limitations and preliminary assumptions that have to be made in order to make the backcalculated process possible. These primarily assumptions are: the layers are homogenous, isotropic, and linear elastic. each structural layer has a uniform stiffness in horizontal direction.

3.3 Derivation of Layer Moduli From Artificial Deflection Data

The linear elastic analysis (LEA) is the most popular method in modeling the pavements moduli as it is simple and the magnitude of the applied load on the pavement is low enough that a linear elastic approximation of the pavement material behavior is deemed suitable [Buchanan, 2007]. The linear elastic analysis is the basic approach in determination of the pavement response under the applied load, conditions, and environment. In linear elastic analysis each individual pavement layer is modeled by its elastic modulus and Poisson's ratio.

3.3.1 Boussinesq's Equations

A set of equations was developed by Boussinesq to calculate the stress, strain and the displacement at the depth 'z' below the center line of a uniform circular load at the radius 'a' from the loading center; for a homogeneous, isotropic, linear elastic, semi-infinite space. The characteristic of Boussinesq' equations can be applied easily to a FWD test with several deflection sensors with offset distances. Many software have utilized the application of the Boussinesq's equations in calculating the pavement layers moduli; they apply the equations iteratively to find moduli values that is accurate for the pavement parameters combination that have been input [Highway Department, 2009].

It is worth mentioning that one important factor, the horizontal strain at the bottom of pavement layers (especially the asphalt layer) is not calculated with the Boussinesq's equations. In fact, there is another method known as "Radius of Curvature", that can calculate it.

3.3.2 Odemark's Method Of Equivalent Thickness

The Boussinesq's method is only practical when assuming that the pavement system is a homogeneous half-space. Such hypothesis is not applicable since the pavement systems are layered structures. The theory developed by Odemark is an approximate method in which the layered system with different layer thicknesses and moduli is transformed in to one equivalent system in which all the layers have the same modulus. This method is named as the "Method of Equivalent Thickness". The adjustment factor, F, is applied in order to comply with the elastic theory agreement. The layers thickness, Poisson's ratio, number of layers and the layers modular ratios affect the adjustment factor directly. The Poisson's ratio can be assumed the same for all layers (0.35). The equivalent thickness is calculated using equation 3-1:

$$H_{eq} = F \times \mathrm{H}_1 \times [E_1/E_2]^{1/3} \qquad \textit{Eq.(3-1)}$$

where,

H_{eq} =The equivalent system thickness,

F = The adjustment factor,

H_1 = Thickness of the layer #1,

E_1 & E_2 = The modular ratio of the layers,

Odemark's method is used in the development of backcalculation programs. Sometimes, Odemark's method is used in coordination with Boussinesq's method. The analysis of a multi-layer pavement system when the layers moduli are known, the layered system can be transformed in to an equivalent homogenous layer with the modulus equal to the modulus of the semi-infinite subgrade layer. Then the stresses, strains, and the displacements within the equivalent layered system can be calculated by applying the Boussinesq's equations. This process is reversed when working with the FWD data as the measured surface displacements at offset distances from the center of the loading plate are used to calculate the moduli of individual pavement layers [Highway Department, 2009].

3.3.3 Hogg's Model

In 1944 Hogg introduced a model through which the subgrade stiffness or the elastic modulus can be determined directly under the imposed load on the surface. The basic assumption of the Hogg model is that the pavement is a two-layer system made of a relatively thin and stiff

layer (as referred to in some texts the “Plate”) resting on an elastic foundation. In fact this two-layered system is used to simplify the typical multilayered elastic system. There is tendency to overestimate or somehow underestimate the subgrade modulus if not knowing which deflection values at what offset distances should be used in the backcalculation models. Hogg model is no exception to this matter. According to removing the estimation bias, Hogg showed that utilizing the deflection value at the center of the loading plate and one of the offset deflection is quite effective. The deflection sensor which measures approximately one-half the central deflection sensor is the objective for this model. Some other substantial factors are considered in the Hogg model: variation in pavement thickness, the ratio of upper layers stiffness to the subgrade stiffness (also known as modular ratio), and the presence of a hard or stiff layer at some depth. Hogg’s Model equations and the relative coefficients as indicated by Stubstad (et al., 2005) are:

$$E_0 = \frac{(1+\mu_0)(3-4\,\mu_0)}{2(1-\mu_0)}\left(\frac{S_0}{S}\right)\left(\frac{P}{d_0\,l}\right) \qquad \textit{Eq.(3-2)}$$

$$r_{50} = r\,\frac{(1/\alpha)^{1/\beta}-B}{\left[\frac{1}{\alpha}\left(\frac{d_0}{d_r}-1\right)\right]^{1/\beta}-B} \qquad \textit{Eq.(3-3)}$$

$$l = \mathrm{y}_0\,\frac{r_{50}}{2} + [(y_0 r_{50})^2 - 4mar_{50}]^{\frac{1}{2}} \quad if\ \frac{a}{l} < 0.2, then\ l = (\mathrm{y}_0 - 0.2mr_{50}) \qquad \textit{Eq.(3-4)}$$

$$\left(\frac{S_0}{S}\right) = 1 - \bar{m}\left(\frac{a}{l} - 0.2\right) \quad if\ \frac{a}{l} < 0.2, then\ \left(\frac{S_0}{S}\right) = 1.0 \qquad \textit{Eq.(3-5)}$$

where,

E_0 = Subgrade modulus under FWD test load,

μ_0 = Poisson's ratio for subgrade material,

S_0 = Theoretical point load stiffness,

S = Pavement stiffness, (P/d_0)

P = Applied FWD load,

d_0 = Deflection at center of FWD load plate,

d_r = Deflection at offset distance r,

r = Distance from the center of FWD,

r_{50} = Offset distance where $(\frac{d_r}{d_0})$ = 0.5,

l = Characteristic length,

h = Thickness of subgrade above apparent hard layer (Table3-1),

I = Influence factor (Table 3-1),

α, β, B= Curve fitting coefficients (Table 3-1),

y_0, m = Characteristic length coefficient (Table 3-1),

$\bar{m}$ = Stiffness ratio coefficient (Table 3-1),

a = Radius of FWD load plate,

Table 3-1 Hogg Model Coefficients By Stubstad (et al., 2005)

Equation	Hogg Model Case	Coefficient	I	II	III
	Assumed depth to hard bottom	$\frac{h}{l}$	10	10	Infinite
Eq.(3-2)	Poisson's ratio of subgrade layer	μ_0	0.50	0.40	All values
Eq.(3-2)	Influence factor (constant)	I	0.1614	0.1689	0.1925
Eq.(3-3)	For ranges of $\frac{d_r}{d_0}$: $r_{50}f(\frac{d_r}{d_0})$>0.70	α β B	0.4065 1.6890 0	0.3804 1.8246 0	0.3210 1.7117 0
Eq.(3-3)	For ranges of $\frac{d_r}{d_0}$: $r_{50}f(\frac{d_r}{d_0})$<0.70	α β B	2.6947E-3 4.5663 2	4.3795E-4 4.9903 3	-
Eq.(3-4)	$L = f(r_{50}, a)$	y_0 m	0.642 0.125	0.603 0.108	0.527 0.098
Eq.(3-5)	$\left(\frac{S_0}{S}\right) = f(a, l)$	$\bar{m}$	0.219	0.208	0.185

3.3.4 Dorman and Metcalf Method

In 1964 Dorman and Metcalf introduced a method to estimate the individual layer modulus of a pavement system consisting of three layers. Dorman and Metcalf developed theoretical design curves based on experimental data derived from in-situ and laboratory testing on three-layered flexible pavements. By studying the curves they found a relationship which predicts the base and the surface layer moduli. The

asphalt layer (surface layer) moduli can be derived from the curve indicating the asphalt moduli and the temperature and the asphalt layer thickness.

When a relatively thin bound surface course plus an intermediate base course layer exist within the pavement structure, the modular ratio between two adjacent layers of unbound material can be used to predict the moduli of the upper bond layer from the subgrade moduli. This is because the effective modulus of the intermediate bound layer (base layer) tends to relate to the subgrade moduli [Heukelom and Klomp, 1962, Dorman and Metcalf, 1964]. Dorman and Metcalf declared that the effective modulus of the combined base and sub-base layer (there may or may not be a sub-base layer) is 2 to 4 times the subgrade modulus. By estimating the subgrade modulus using any regular methods or laboratory testing, the base modulus can be calculated by the modular ratio between the base and the subgrade layer, E_2/E_3, (E_2 is the effective modulus of the combined base and sub-base layer, and E_3 is the subgrade modulus).

The modulus relationship developed by Dorman and Metcalf is:

$$E_{Base} = 0.2 * h_2^{0.45} * E_{Sub} \qquad \textit{Eq.(3-6)}$$

where,

E_{Base} = Dorman and Metcalf Base modulus, (Mpa)

h_2 = Thickness of the base layer, (mm)

E_{Sub} = Subgrade modulus, (MPa)

Although imperfect, the Dorman and Metcalf method had shown far more stable and realistic results in comparison with the traditionally backcalculated moduli (Stubstad et al., 2009 , Dorman and Metcalf, 1964).

3.3.5 Artificial Neural Network

Another interesting method in derivation of the layer moduli is the Artificial Neural Network (ANN). Meier (et al., 1994) applied the ANN for the first time in the context of backcalculation of layer moduli. An artificial neural network is a collection of highly interconnected simple processing elements that can be trained to learn any function and to approximate a complex matter by having a repeated exposure to solved examples of the function. The ANN can be adjusted (trained) in a way that a particular input data leads to a desired output. In FWD data analysis, ANN can learn to map the deflection basin along with the pavement moduli measured independently before the FWD test. If such independently measured parameters (layer moduli, layers thickness, and etc.) do not exist, they can be produced by solving the forward problem with many different combinations of pavement layers properties. Then a neural network can learn to map this manually produced deflection basin back into their

corresponding moduli values. After the training process the ANN can use the solutions for unknown deflection basins (not the ones it had been trained with). The advantages of this method are the speed, accuracy, and the lack of requirement for a highly experienced operator.

3.3.6 Finite Element Modeling

The most recent approach in determining the layers stiffness is through the two or three-dimensional Finite Element Models. Although the finite element modeling approach seems reasonably accurate and precise in comparison with the Boussinesq's equations or the Odemark's method, not every operator can perform such technique since it is mostly applied in advanced research.

The Boussinesq's equations, Odemark's method, and the Hogg's model, have been modified or even combined by some researchers in order to use them into more realistic cases in terms of different types of pavement structures and type of surface layers. Some of these modified yet combined methods are used in either backcalculation or direct estimation process.

3.4 Backcalculation Techniques

Before describing some of the techniques employed in backcalculation process, it is essential to mention that in terms of the nature of the FWD/LWD loading, there are two backcalculation

approaches for the system of pavement-subgrade model: elasto-static and elasto-dynamic models. Both methods operate by characterizing the pavement system with an equivalent surface thickness and assume that the subgrade layer is an elastic half-space. Most of the backcalculation techniques which are using the peak values of the load-deflection of the sensors are based on the elasto-static models in spite of the dynamic nature of the FWD/LWD loading. The elasto-static model assumes that the FWD/LWD load is applied statically. Regardless of the dynamic characteristic of the FWD loading, the elasto-static model is vastly used in backcalculation and pavement engineering because it is more simple to use and computationally efficient. Although some studies have been performed in order to prove that elasto-dynamic models are more accurate in backcalculation of the pavement parameters, the results have proven that the moduli derived from elasto-dynamic backcalculation are as scattered as the results from the elasto-static models. However, the backcalculation process related to elasto-dynamic is more complicated yet no significant differences have been observed. In fact, the comparison study performed on the FWD simulation that has been analyzed with both elasto-static and elasto-dynamic models, has shown reasonable results for both models. Therefore, it was concluded that there is no superiority in using either of these two models (Nezhentsev, 2009, Ameri et al., 2009)

In terms of deflection data application in derivation of the layers modulus and other deflection basin's parameters, two major methods are used; each uses the deflection data differently:

1) Radius of Curvature Method: In this method, to determine the top layer moduli and the intermediate layer moduli (if present), the center deflection and the curvature of the deflection basin under the loading plate is considered. The moduli of the subgrade is adjusted according to the stress level under the center of loading; then the outer deflections are checked to examine the moduli values. If not satisfied within the defined tolerance, the moduli are recalculated.
2) Deflection Basin Fit Method: In this method instead of matching up the moduli calculated from one deflection sensor and then adjusted for the next outer deflection, the whole calculated (synthetic/arbitrary data base) deflection profile will be closely match to the measured deflection profile. The difference between the calculated profile and the measured profile is normally used as the convergence criteria in the iteration process and can be defined manually.

Apart from how the deflection basin profile is being analyzes or whether the impulse load is being considered statically or dynamically,

after the FWD measurement , the experimental data should be compared with the synthetically produced data base for derivation of the backcalculated pavement parameters. In this process, the measured deflection values should be match up with the calculated deflections in the data base as close as possible. This comparison process can be performed through different approaches:

- Closed-form solutions (Hall and Mohseni, 1991, Scriner et al.,1973),
- Regression and data base search (Ali and Khosla, 1987, Anderson, 1989, Chou and Lytton, 1991, and Roque et al., 1998),
- Optimization techniques (Bush and Alexander, 1985, Harichandran et al., 1993, Sivaneswaran et al., 1991),
- Artificial neural networks (Meier et al.,1994, Mehmet Saltan et al., 2012),
- Finite element modeling (Grasmick, 2013),
- The iterative mathematical process and so many other methods considering a combination of these.

3.5 Backcalculation Software Programs

In general, two types of software exist to perform a complete backcalculation process. The first software known as the data based method is to create a data base (synthetic data base) relative to the site being tested. The data based method software programs use forward calculation technics to produce a synthetically designed deflection basin data base. The second part of program can use the data base along with an interpolation scheme or a formulated regression equation to compute the layer moduli from the deflections.

The second types of the backcalculation software are those that use the forward calculation technics (mostly a linear-elastic program) iteratively. They compare the measured deflections with the calculated deflections to find the best deflection basin match.

Following, are a few examples of some of the known software:

1) WESLEA*:* It was first introduced by Van Cauwelaer (et al.,1989) as a structural design procedure for the U.S. Army Engineer Water Experiment Station (WES) for Linear Elastic Analysis (LEA) of flexible and rigid airport pavement. The software uses forward calculation subroutines to generate a data base of deflection bowl by assuming different modular ratios. WESLEA is based on multilayer linear elasto-static

theory which calculates the deflection bowls for a pavement of up to five layers and considers the multiple loads and variable interface conditions. The created database by WESLEA is being used in several backcalculation software. The actual modulus backcalculation program that is produced with the WESLEA is WESDEF. WESDEF can combine the WESLEA results with optimization routine to calculate the layer moduli. Another example of such programs is the database generator program named BISAR and the backcalculation program BISDEF that was produced to be used with it.

2) MODULUS: This program was developed at Texas Transportation Institute (TTI) for the Texas DOT. MODULUS functions as a unit and it uses the WESLEA for data base creation and a pattern search technique for the determination of the set of moduli that can best fit the measured deflection basin data from the FWD test. The MODULUS can operate 7 deflection sensors and it can process up to four layers (with or without bedrock). It is a very simple program to use and it only requires the user to identify the layers materials and thickness; then the program

itself will suggest relevant moduli ranges and Poisson's ratios.

3) ELMOD: The Evaluation of the Layer Moduli and Overlay Design program or ELMOD was developed by Dynatest Consulting Incorporation. ELMOD uses the Odemark-Boussinesq's transformation for data base creation and the iterative method for the backcalculation of the layer moduli. ELMOD has different backcalculation modes.
   - Radius of curvature, with this approach up to four layers can be analyzed.
   - Deflection basin fit, with this method up to 5 layers can be analyzed.
   - FEM/LET/MET. This option can use either the Finite Element Method, or the Linear Elastic Theory based methods (such as WESLEA), or the Method of Equivalent Thickness.
4) EVERCALC: This software was developed at the University of Washington for Washington DOT. It uses WESLEA for forward analysis of a user defined deflection basin and then uses a modified Gauss-Newton algorithm for optimization of the backcalculation results.

Ameri (et al., 2009) compared three elasto-static backcalculation programs: MODULUS, ELMOD, and EVERCAL. The FWD data have been gathered from different test sites. The author have compared the results and the performance of each test with all three programs. Moreover, the laboratory soil mechanic tests on subgrades have been held as basis of comparison of the layers moduli derived from different software. The key input parameters for all three software were as follow:

- The layer thickness. The thickness of each layer has been measured at each testing station. It worth mentioning, that all the pavement structures at testing sites have the same composition: an asphalt surface spread on top of a crushed stone base layer.
- Moduli ranges
- Poisson's ratio

The results of a SHRP (States Highway Rehabilitation Program) report have been used for assumption of the layers moduli range and Poisson's ratio of each layer, and the subgrade has been identified based on the CBR values and correlation relation with the resilient modulus of the subgrade measured in the laboratory. The results of the comparison were:

- The average moduli of the surface layer determined by all three programs showed good consistency.

- The resilient modulus of the subgrade calculated by ELMOD was a bit over estimated.
- The results of all three layers parameters calculated by EVERCALC and MODULUS was consistent.
- The presence of the bedrock is predictable in MODULUS and ELMOD. But the process of adjusting the depth of bedrock according to reasonable range of the subgrade moduli is faster in MODULUS.
- The prediction of the subgrade modulus at the beginning of the backcalculation is very critical. All the estimations after that depend on this prediction.

In MODULUS, this subgrade prediction at the start of the process is within the modulus range anticipated for each site, and it was also in compliance with the resilient modulus estimation based on the CBR values. The MODULUS program was suggested to be more accurate and easy to use among all three software programs.

3.6 Input parameters for deflection calculation with software

In deflection calculation process, the software program assumes primarily input ranges of layer moduli and Poisson's ratio. Among these two variables, Poisson's ratio has less significant effect on the calculations. The expected layer moduli range or the seed moduli (some

programs use seed moduli), are mostly focused in pavement modeling programs. Chou (et al., 1989) suggested a predefined moduli value in a tabular form (Table3-2). The maximum and the minimum values suggested for the subgrade resilient modulus is 50,000 psi and 10,000 psi respectively.

Table 3-2 Moduli Values Suggested By Chou (et al., 1989)

Climatic Condition				
Material	Dry (psi)	Wet (No freeze) (psi)	Wet (Unfrozen) (psi)	Wet (Frozen) (psi)
Clay	15,000	6,000	6,000	50,000
Silt	15,000	10,000	5,000	50,000
Silty or Clayey sand	20,000	10,000	5,000	50,000
Sand	25,000	25,000	25,000	50,000
Silty or Clayey Gravel	40,000	30,000	20,000	50,000
Gravel	50,000	50,000	40,000	50,000

Buchanan (et al., 2007) suggested that the subgrade modulus can be estimated using any correlation equations if no further testing of subgrade material is possible. The maximum value of 60,000 psi and the minimum value of 15,000 psi should be used for the resilient modulus using any method to predict the subgrade resilient modulus.

Wiseman (et al., 1987) derived the CBR value of the soil from the information sources mentioned and introduced a correlation equation between the CBR and the field modulus values.

$$E_{(psi)} = 1500CBR \qquad \textit{Eq.(3-7)}$$

3.7 Post-processing of The FWD Calculated/Measured Deflection Data

In spite of the extensive amount of thought put in to the input assumption for a simulating pavement model of the testing site, sometimes occurrence of uncertainties and inefficiencies in the created data base may seem inevitable. Such deficiencies cannot be address unless the FWD field test is complete. It is during the backcalculation process that the existence of any inaccuracy, whether from the input assumptions or the measured data, may appear. Probability of such phenomenon, calls for a post-processing of the measured FWD data for a preliminary examination of the data relevancy (Chou and Uzan, 1989).

Several steps should be followed after the FWD test is complete to make sure that the whole process may not lead to erroneous the results and conclusions:

1) The basin shape should be examined in order to discover any malfunctioning sensors or irregularity of the measured basin. Sometimes the pavement surface distresses (large cracking or void underneath the surface layer, rutting) or pre-

existing conditions (drainage condition, high/low temperature) may cause some incorrect data record.

2) The subgrade modulus should be estimated due to simple methods described earlier.
3) A linear-elastic program should be called to search through the data base created previously to find a best set of layer moduli that best fit the measured deflection basin. Then the backcalculated moduli and the corresponding deflection basin should be compared with the preliminary information (described in the knowledge base expert system) that exists about the site being tested to make sure that the results are within expected range. If there is not a satisfactory match between the deflection basins and retrieved moduli, it may occur because of a strong effect of nonlinearity in material properties or incorrect layer thickness input or even incorrect deflection measurement. This problem can be address by performing a correction routine in the created data base, site observation for surface distresses and, sometimes the confirmation site test to reassure the measurement validity.
4) There is a need to conduct destructive tests in some critical locations. These locations can be identified from the

backcalculated results. Sometimes the layer moduli are surprisingly lower or higher than expected for the specific sections. In these situations, even though after the confirmation tests have been performed, the destructive test should be done to verify the actual layers thickness, materials, conditions, and etc. It is only through destructive tests that under-surface deficiencies can be identified in places that the accuracy of the moduli is crucial. After the destructive test is performed, the data base should be corrected and the backcalculation process should be repeated.

3.8 Direct Estimation of Layer Moduli

A Direct Estimation method is considered as an individual moduli derivation method. It can be best described by the one that has been introduced by Stubstad et.al. (2005). Of course the 2005 model is not the most recent direct estimation method but it is the one that can be considered as a fully developed one. This method is independent from the backcalculation proceeding. Stubstad's direct estimation procedure is a new approach that can determine the layers elastic modulus from the in-situ load-deflection data but in an utterly distinct way. In the direct

estimation, method moduli values are calculated directly from the load-deflection data using a closed form equations without going through any iteration process. The closed form equations can be used for both subgrade and the bound surface course for both flexible and rigid pavement systems. The intermediate layers or the base course moduli can also be estimated by applying the commonly used modular ratios between the adjacent layers.

To verify this method the entire Long Term Pavement Performance data set (LTPP) backcalculation results up until 1998 have been processed again with this direct estimation method. It was expected that, because both the direct estimation and backcalculation methods are using the same data set of an identical test device, the derived moduli results would be in a reasonable range in comparison. But it showed that the moduli values resulted from the direct estimation were more stable than the backcalculated results on a section-by-section basis. Also the direct estimation moduli values were more reasonable in most cases (Stubstad et al., 2005).

The forward calculation (direct estimation) method first has been introduced and published by Wiseman and Greenstein in 1944 and it has been incorporated into spreadsheet format more than 20 years ago. This method utilizes the Hogg model to determine the subgrade modulus from

the center deflection data of the FWD plus one selected offset sensor deflection reading. After several experiments and analysis, Wiseman and Greenstein found that the offset distance where the deflection is one half of that under the center of the load plate is where the biases inherent into simplified two-layered Hogg model in a way that the subgrade modulus is neither over nor under estimated as it may happen in backcalculation process [Stubstad, et al., 2005].

Another forward calculation (direct estimation) method has been developed in 2002 also by Stubstad and has been evolved in a FHWA publication in 2006 (Stubstad et al., 2006). The method is called AREA. AREA method as described in FHWA (Stubstad et al., 2006) is the method that can determine the bound surface layer modulus from calculating the composite modulus of the entire pavement structure layers using the AREA factors, the center deflection, and also the three of the FWD deflection readings (three deflection sensors readings for flexible pavement and four deflection sensors readings for rigid pavement) and the upper layer thickness (bound layer).The AREA factor is the area of a vertical slice of the deflection basin, starting from underneath the center deflection sensor up to the certain deflection sensor. It is usually named with the deflection sensor that is chosen for the calculation purpose. There are equations developed by Stubstad (et al., 2006) that are calibrated for

both rigid and flexible pavements using the AREA concept. The rigid pavement AREA concept was first introduced by Hoffman and Thompson in 1981, and the flexible pavement AREA approach is a relatively new method by Stubstad. The bound surface modulus calculated by AREA method can be used along with other methods calculating all the pavement layers moduli (when determination of subgrade and intermediate layer are also desired). The AREA method equations are as follow:

For rigid pavement,

$$A_{36} = 6 * [1 + 2\left(\frac{d_{12}}{d_0}\right) + 2\left(\frac{d_{24}}{d_0}\right) + \left(\frac{d_{36}}{d_0}\right)] \quad \textit{Eq. (3-7)}$$

$$AF_{PCC} = [\frac{(k_2 - 1)}{\left\{k_2 - \left(\frac{AREA_{36}}{k_1}\right)\right\}}]^{1.79} \quad \textit{Eq. (3-8)}$$

$$E_{PCC} = \left[E_0 * AF_{PCC} * {k_3}^{\left(\frac{1}{AF_{PCC}}\right)}\right] / {k_3}^{2.38} \quad \textit{Eq. (3-9)}$$

For flexible pavement,

$$A_{12} = 2 * [2 + 3\left(\frac{d_8}{d_0}\right) + \left(\frac{d_{12}}{d_0}\right)] \quad \textit{Eq. (3-10)}$$

$$AF_{AC} = [\frac{(k_2 - 1)}{\left\{k_2 - \left(\frac{AREA_{12}}{k_1}\right)\right\}}]^{1.35} \quad \textit{Eq. (3-11)}$$

$$E_{AC} = \left[E_0 * AF_{AC} * k_3^{\left(\frac{1}{AF_{AC}}\right)}\right] / {k_3}^2 \qquad \textit{Eq. (3-12)}$$

Where,

A_{36} , A_{12} = AREA beneath the first 36 inch (12 for flexible pavement) of the deflection basin,

d_i = Deflection measured i inch from the central geophone,

AF_{PCC} = AREA factor,(the improvement of AREA from 11.04 to the 1.79 power,

AF_{AC} = AREA factor (the improvement of AREA to the 1.35 power,

k_1 = 11.04 for rigid pavement, 6.85 for flexible pavement,

k_2 = 3.262 for rigid pavement, 1.752 for flexible pavement,

E_{PCC} = Modulus of the upper PCC bound layer (rigid pavement),

E_{AC} = Modulus of the upper AC bound layer (flexible pavement),

E_0 = Composite modulus of the pavement structure,

k_3 = Thickness ratio of upper layer thickness / load plate diameter [h_1/(2*a)],

a = Radius of the FWD load plate,

Direct estimation methods (forward calculation the literature) have some advantages:

- Each load-deflection basin offers a unique solution for the bound surface moduli and the subgrade moduli. No moduli values are depended upon each other.
- It is simple to be performed by users.
- In comparison with the backcalculation, direct estimation method produces less scatter in the data for the same test sections and layers.

There are some drawbacks of the moduli direct estimation methods:

- The subgrade modulus and the surface course moduli are calculated independently from one another. Because of this matter, the calculated moduli values for each layers, are not completely corresponding with the composite modulus calculated from the total center deflection.
- The original method has been introduced for two-layered system. In presence of an intermediate third layer (granular base layer), the third layer moduli can be calculated differently. For 3-layered pavement systems, the surface and subgrade moduli are calculated, assuming that the subgrade and surface moduli are fixed and correct. Then the center

deflection should be fit to the remaining unknown stiffness share that we assume is for the base layer (intermediate layer). In another term, the moduli of the surface and subgrade are subtracted from the composite modulus of the pavement. Then the remaining stiffness and deflection (under the load center) are fit together assuming that they are the modulus and deflection of the base layer. In this case it is certain that this approach suffers from the same problem that is normal in the backcalculation process, and that is the dependency of the layers moduli to one another. It is possible to use the modular ratio theory of Dorman and Metcalf (1987), between the subgrade moduli (calculated through the direct estimation method) and the unbound base layer (discussed in part 3.9).

3.9 Relevant Studies Focusing on Layer Moduli Direct Estimation

The forward/back calculation methods mentioned earlier in this chapter are entirely based on the FWD deflection basin data, that normally contains data recorded by at least seven geophones. Since the LWD collects data from a maximum of three geophones and has a shallower depth of influence, lighter drop weight, limited combination of the offset distances, the methods developed for FWD deflection analysis cannot be

used for LWD deflection analysis. Only a few recent studies have investigated methods that could be applicable to the LWD deflection basin data.

Stubstad (et al., 2009) introduced a new method for calculating layered-elastic moduli from the LWD deflection basin. This study has been directed by Carl Bro A/S pavement consultant incorporation (the manufacturer of PRIMA100). Stubstad's method for LWD is an improved and calibrated method of the method he previously developed for the FWD (Stubstad et al. 2005). The procedure designed for the LWD deflection basin is called Deterministic Empirical Backcalculation (DEB). This DEB method can also be referred to as a forward calculation method.

This method utilizes closed-form solutions to calculate at least two stiffness (modulus) values on a point by point basis. Three deflection readings of LWD at appropriate offset distances are required. The offset distances are depending on the structure being tested and the diameter of the loading plate (7.88 in and 12 in).The 12 inch plate is used for the unbound materials. For bound materials both plates can be used. The first sensor must be at the center and the two others at required distances.

The parameters calculated during the DEB process are:

1) The stiffness of the upper bound layer or layer #1, which should be relatively thin in order to obtain reliable results due to LWD lower load level in compare with the FWD.
2) The Stiffness of unbound layer as layer #1 (or layer #2 if layer #1 is consists of bound materials).
3) The stiffness of the subgrade layer under the loading plate using a modified Hogg model. The upper portion of the subgrade is critical in this part.
4) The depth of the stiff layer or unyielding layer can be identified beneath the subgrade.

Because the LWD is performed mostly on unbound materials, the Hogg model has to be modified to fit the data. Originally, the Hogg model considers the upper layers as a simplified single layer above the subgrade. Such assumption should be made only if there is bound material in order to be able to consider an effective elastic modulus for the equivalent layer.

The DEB method has been developed to derive two crucial layered elastic moduli, the elastic moduli of the surface course and the upper portion of the subgrade. The DEB routines used for derivation of the each one of these two layers elastic moduli are completely discrete from one

another, so that the empirically derived backcalculated moduli value of one layer (no matter how high or how low they are) can not affect the other layer's moduli prediction accuracy. This is because the subgrade modulus affects the deflections measured at larger distances from the loading center, while the surface course modulus is a function of the near center loading-deflection [Stubstad et al., 2009].

In fact, the DEB method is suitable for three unknown pavement layers with the upper layer of a thin bound layer. The Dorman-Metcalf modular ratio relationship is being used for the calculation of the layer #2 modulus which is an unbound layer, based on the subgrade modulus calculation through a modified Hogg model. The DEB method is different from the regular backcalculation process because it utilizes the closed-form solution. Neither seed moduli value nor multiple iteration processes are needed for layers elastic stiffness of the pavement system.

The independently calculated moduli of the layers may not be perfectly consistent with respect to the total center deflection. The drawback of this method when applied to the three-layered pavement system is that when an unbound material layer exists between the subgrade and the upper bound layer, the user must fit the center deflection to the stiffness of the unbound base layer after assuming that the calculated moduli of the upper bound layer and the subgrade layer are

both correct. Therefore, as for the conventional backcalculation, in the DEB method the modulus of one layer will depend on the accurate estimation of the moduli of the other layers.

A study by Kumlai (et al., 2013) recommends a set of equations that compute the stiffness of the layers directly from the FWD surface deflection data. This method is a direct calculation procedure and can handle a four-layer flexible pavement system (Surface course, base, sub-base, subgrade). For the first step, a number of deflection basin data base is generated by a layered-elastic computer model (Everstress 5.0) assuming variable layer thicknesses and layer moduli for a four layered system. Then, the best corresponding deflection parameters and the most relevant equations have been found during statistical analysis process to determine the elastic modulus of each layer. Model verification of the final equations has been performed employing the FWD and a portable seismic pavement analyzer (PSPA).

Because the layer moduli and thickness influence the deflection shape, only these two factors have been considered as variables in the proposed equations. Other parameters such as Poisson's ratio and load magnitude have been considered as constants in Kumlai's research. In order to simplify the model, the non-linear and non-elastic behaviors of the pavement materials have not been considered.

To find the relationship between the deflection parameters and the elastic modulus of the layers, Kumlai has used linear regressions with logarithmic transformation in order to reduce the non-linearity effect of the deflection data in the final results. The input variable used in data base generation are:

1) Four layer moduli assumed for the surface layer, base, sub-base, and the subgrade.
2) The thicknesses of three layers.
3) The Poisson's ratio is considered as 0.45 for the subgrade and 0.35 for other layers materials.
4) Loading plate diameter is 300mm (recommended by ASTM 2005).
5) The number of generated deflection basins have been contained through a DOE technic (Design of Experiment).

The proposed equations (Eq. 3-13 to 3-16), have been tested according to the highest coefficient of determination (R-square) they could provide, and the equations have been evaluated using actual FWD deflection data. The estimated layers moduli have reasonable relationship with the moduli determined with backcalculation models such as Evercalc (Kumlai et al., 2013).The equations are as follow:

$$\log(E_1) = 4.674 - 1.165\log(\Delta d_{10-20}) + 0.901\log(\Delta d_{30-45}) - 0.202\log(\Delta d_{150-180}) - 0.033H_1 \quad \textit{Eq. (3-13)}$$

$R^2 = 0.367$

$$\log(E_2) = 5.629 - 1.450\log(\Delta d_{20-30}) - 0.032H_1 - 0.007H_2 \quad \textit{Eq. (3-14)}$$

$R^2 = 0.813$

$$\log(E_3) = 5.355 - 3.427\log(\Delta d_{45-60}) - 0.028H_2 - 0.027H_3 + 1.172\log(\Delta d_{20-30}) + 1.371\log(\Delta d_{150-180}) \quad \textit{Eq. (3-15)}$$

$R^2 = 0.803$

$$\log(E_4) = 3.176 - 0.956\log(\Delta d_{150-180}) \quad \textit{Eq. (3-16)}$$

$R^2 = 0.993$

where,

E_n = Moduli of the layers # n, (MPa)

H_n = Thickness of layer # n, (cm)

$\Delta di - j$ = di-dj (μmm)

According to the relatively low R-square value of the Eq.(3-13), the authors discover that the AASHTO's effective modulus (E_p) is an excellent transfer variable to determine E_1. E_1 now can be estimated using the

equation Eq. (3-17). The represented equation is the relationship between the product of E_p and pavement thickness (H_T) and the moduli of the three pavement layers yield a high R-square value.

$$E_p H_T = -4467.933 + 0.490 E_1 H_1 + 1.229 E_2 H_2 + 0.653 E_3 H_3 \qquad \textit{Eq. (3-17)}$$

$$R^2 = 0.918$$

where,

E_p = Equivalent modulus of the pavement,(MPa)

H_T = Total Thickness of layers # 1, 2, and 3, (cm)

Chapter 4

Research Methodology and Analysis

4.1 Introduction

This study developed a method to estimate directly the elastic moduli of three-layered flexible pavement system from Light Weight Deflectometer deflection data. The direct computation method can be easily programmed into the palm processors (Palm Pilot) of the Light Weight Deflectometers. The direct computation of the layers elastic moduli is in form of set of equations. Unlike for the backcalculation methods, no iteration sequence is necessary. Therefore, no post-processing of the data is needed. The plugged in equations can be of a primary assistance in flexible pavement stiffness evaluations. This chapter provided the details of the development of the equations that compute the layer moduli from the LWD deflections recorded by three sensors.

4.2 Assembly of the Surface Deflection Database

The development of the equations that estimate the layer moduli was done in two steps:

1) A database of surface deflections at the same offset as that of the LWD geophones was developed by using the linear-elastic pavement response model WinJULEA. The layer moduli, layer

thickness and LWD load were the inputs to the WinJULEA software.

2) A multi-linear regression analysis was conducted on the database to derive the modulus prediction equations.

The pavement systems modeled using WinJULEA have a 2 to 4 inches thick asphalt concrete wearing layer and a 4 to 8 inches of compacted granular base layer. Two different deflection data sets have been generated using WinJULEA (Table 4-1).

Table 4-1 Pavement Systems Modeled With WinJULEA

Dataset	Asphalt Layer Thickness, H_1 (in)	Base Layer Thickness, H_2 (in)	Subgrade Thickness	Geophones Offsets (in)	Load Plate Diameter (in)
1	2.0 and 3.0	4.0, 5.0 and 6.0	infinite	0.0, 9.0 , 18.0	8.0
2	3.0 and 4.0	4.0, 6.0 and 8.0	infinite	0.0, 12.0 , 24.0	12.0

- The first deflection data set has been generated for the pavement system with 2.0 and 3.0 inches of asphalt concrete surface layer and the 4.0, 5.0 and 6.0 inches of granular base layer, resulting in six combinations of layer thicknesses.. The generated data set for this pavement system is utilizing three geophones deflection data of the offset distances of 0, 9 and 18 inches from the central geophone (0, 9, 18 in) and an 8 inch diameter loading plate.

- The second set of deflection data has been generated for the pavement system of 3.0 and 4.0 inches thick asphalt concrete surface layer and the 4.0, 6.0 and 8.0 thick granular base layer. The generated data set for this pavement system is using the 12 inch loading plate and three geophones at the offset distances of 0, 12 and 24 inches from the central geophone (0, 12, 24 in). For thicker surface layers, bigger geophone offsets and loading plates must be used to capture the influence of the subgrade layer.

It was considered that the use of LWD on flexible pavements with an asphalt surface layer thicker than 4.0 inches is impractical since the measured deflections are too small. Also, for pavements with an asphalt surface layer thinner than 2.0 inches and loading plate of 8.0 inches or larger, the linear elastic theory cannot accurately estimate the surface deflections for a structure with known layer thicknesses and moduli.

The datasets were built based upon the assumptions and input values shown in Table 4-2.

Table 4-2 Input Values and Assumptions In Data Set Generation

Layers	Poisson's Ratio	Modulus, E*i* , MR (ksi)	Modular Ratio, m_i=E*i*/MR
Asphalt	0.35	200-3,000	10-200
Base	0.40	100-500	5-50
Subgrade	0.45	10	-

The input values included in the WinJULEA calculations were:

- The subgrade layer thickness used was 200 inches as to be much thicker that the pavement layers.
- The assumed Poisson's ratios for the surface, base and subgrade layers were 0.35, 0.40, and 0.45 respectively.
- The modulus of the surface layer, E_1, was varied between 200 and 3,000 Ksi, while the modulus of the base layer, E_2, was varied between 100 and 500 Ksi.
- The subgrade resilient modulus, MR, was fixed at 10 Ksi. As Because the WinJULEA program is a linear elastic program, under the same loading condition, there is an invers proportionality between the most outer deflection (at 18.0 and 24.0 inch offset) and the moduli of the subgrade layer. The 1993 AASHTO Guide for Design of Pavement Structures gives a formula for estimating the subgrade layer moduli from the value of the outer deflection. Also, there is an inverse proportionality between the deflection values and the layer moduli values; if all moduli increase by a factor, all deflections reduce by the same factor.
- The moduli ratio E_1/MR was varied between 10 and 200 while the moduli ratio E_2/MR was varied between 5 and 50.

- The impact load of 3,000 lbf was considered. This value can be normally achieved with the LWD equipped with the 33.06 lb (15kg) weight and raised to the maximum height. Under this load, the vertical stresses induced at the top of the subgrade layer are between 7 – 15 psi (NCHRP, 2008), similar to those that develop at the top of the subgrade layer for a conventional flexible pavement loaded by half of a standard axle (9,000 lbs wheel load).
- The load area considered was a circular area with the same diameter as that of the LWD loading plate. For this study two load plates have been used, with 8.0 and 12.0 inch diameter.
- The evaluation points were selected at the surface of the pavement, at the location of the LWD geophones.

After completing the input data, the WinJULEA program is run. Each deflection data set computed with WinJULEA has been stored in a Microsoft Excel file for further analysis. The WinJULEA user input screen is shown in Figure 4-1.

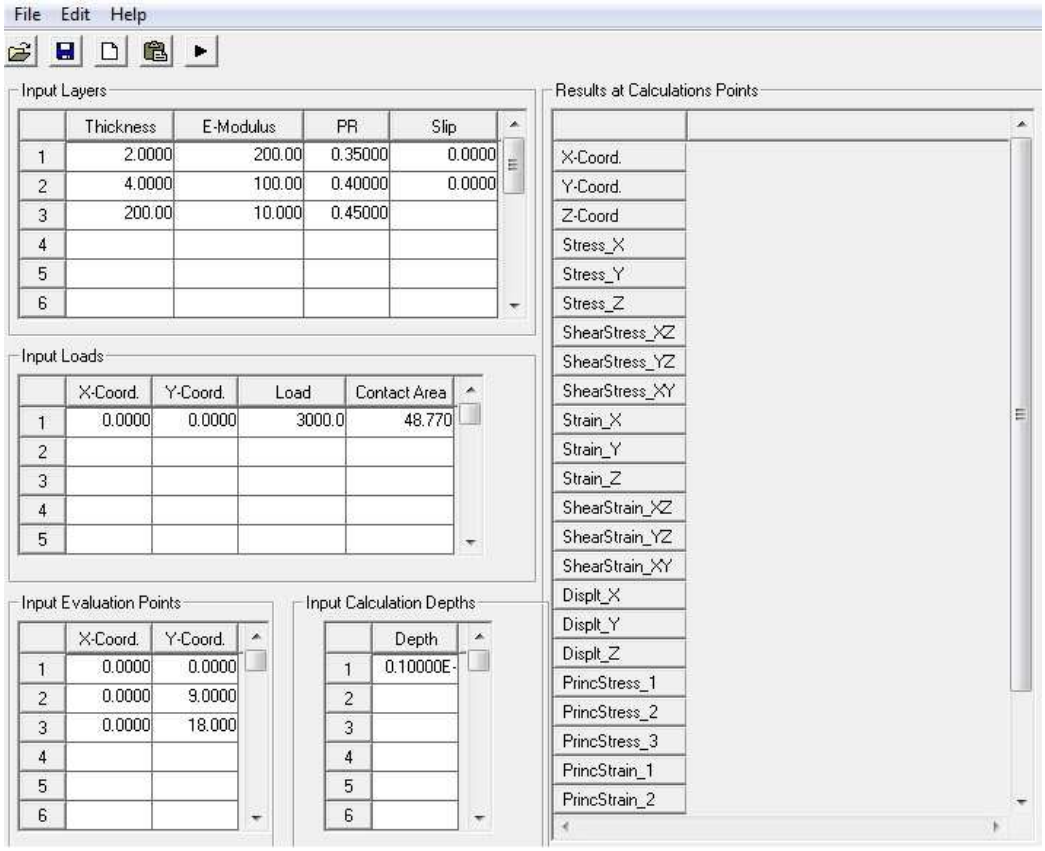

Figure 4-1 WinJULEA Input Screen

An example of the WinJULEA output window is given in Figure 4-2.

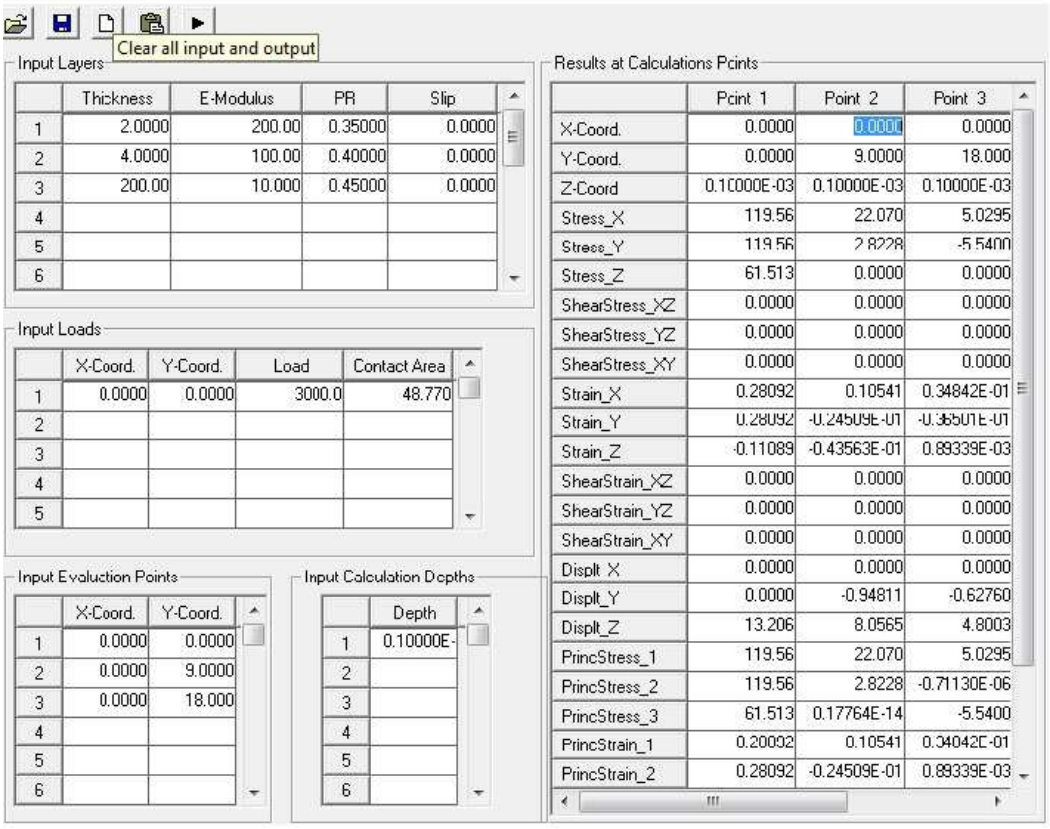

Figure 4-2 WinJULEA Deflection Calculation Results

4.3 Multi-Linear Regression Analysis

The datasets was built after the WinJULEA runs. The total number of deflection basin data runs with WinJULEA contained 2,300 observations. The data were organized in tabular form that included:

- Layer thicknesses H_1 and H_2 (thickness of the surface and the base layer respectively)
- Layers moduli E_1 , E_2 and MR.

- From these values, the moduli ratios $m_1 = E_1/MR$ and $m_2 = E_2/MR$ were computed.
- Calculated deflections, D_0, D_9 and D_{18} for the first data set and D_0, D_{12} and D_{24} for the second data set.
- From the deflection values, the deflection ratios, $d_1 = D_0/D_{18}$ and $d_2 = D_9/D_{18}$ were computed for the first dataset. The ratios $d_1 = D_0/D_{24}$ and $d_2 = D_{12}/ D_{24}$ were computed for the second dataset.

A multi-linear regression analysis was conducted using the statistical analysis software (SAS 9.3) and Microsoft Excel. Regression models relating m_1 and m_2 to d_1 and d_2 were sought. A pair of equations has been developed for each pavement dataset (Equations 4-3, 4-4, 4-5, and 4-6).

4.4 Estimation of Pavement Layer Moduli

The estimation of elastic moduli of pavement layers from the surface deflections measured with the LWD is done in following steps:

Step 1: The resilient modulus of the subgrade layer is estimated directly from the outer deflection (D_{18} or D_{24}) with the relationship recommended by the 1993 AASHTO Guide for Design of Pavement Structures (Eq. 4-1 and 4-2).

$$MR = \frac{P(1-\mu^2)}{\pi * r * dr} \qquad \textit{Eq. (4-1)}$$

where,

MR = Elastic modulus of subgrade, psi

dr = Deflection at distance r from applied load, inches

μ = Poisson's ratio of the subgrade

P = Load, pounds

r = Radial distance from the load, inches

Assuming the Poisson's ratio of the subgrade equal to 0.5, Eq.(4-1) is reduced to Eq.(4-2) :

$$MR = \frac{0.24 * P}{d_r * r} \qquad \textit{Eq. (4-2)}$$

Step 2: The deflections ratios, d_1 and d_2, are computed from the measured deflections.

Step 3: The moduli ratios, m_1 and m_2 are computed from the equations 2, 3, 4, and 5 depending if the surface layer thickness, H_1, is between 2.0 and 3.0 inches (relatively thin pavement) or between 3.0 and 4.0 inches (thicker pavement).

For thinner pavement system, with H_1= 2.0 to 3.0 inches and H_2 of 4.0, 5.0 and 6.0 inches, the following relationships provided the best fit:

$$m_1 = A_1 + A_2.\left(\frac{1}{{d_1}^2}\right) + A_3.\left(\frac{1}{{d_2}^2}\right) + A_4.\left(\frac{1}{{d_1}^{0.25}}\right)$$

$$+A_5.\left(\frac{1}{{d_2}^{0.25}}\right) + A_6.\ H_1 + A_7.H_2 \qquad \textit{Eq. (4-3)}$$

$$m_2 = A_1 + A_2.\left(\frac{1}{d_1}\right) + A_3.\left(\frac{1}{d_2}\right) + A_4.\left(\frac{1}{{d_1}^{0.5}}\right)$$

$$+A_5.\left(\frac{1}{{d_2}^{0.5}}\right) + A_6.{d_2}^2 + A_7.H_1 + A_8.H_2 \qquad \textit{Eq. (4-4)}$$

where,

m_1 and m_2 = Moduli Ratios,

A_1 to A_8 = Regression Coefficients,

d_1 and d_2 = Deflection Ratios,

H_1 and H_2 = Surface and base layer thicknesses, in inches

The regression coefficients values for Eq. (4-3) and Eq. (4-4) are given in Table 4-3.

Table 4-3 Regression Models For The Pavements With 2.0-3.0 Inch Asphalt Layer

	To compute m_1		To compute m_2	
	Coefficient	p-value	Coefficient	p-value
A_1	-24,951	<0.0001	14,710	<0.0001
A_2	7,998.9	<0.0001	-803.82	<0.0001
A_3	-14,520	<0.0001	160,16	<0.0001
A_4	-6,527.9	<0.0001	657.72	<0.0001
A_5	38770	<0.0001	-29912	0.0062

Table 4-3 Continued

A_6	-82.095	<0.0001	-435.15	<0.0001
A_7	63.78	<0.0001	-9.743	<0.0001
A_8	0	-	-12.16	<0.0001
R-square	0.8138		0.923	
Root MSE	31.99		3.41	

For the thick pavement system where, H_1= 3.0 and 4.0 inches and H_2= 4.0, 6.0 and 8.0 inches, the following relationships provided the best fit:

$$\mathrm{m}_1 = A_1 + A_2.d_1 + A_3.d_2 + A_4.\left(\frac{1}{{d_1}^{0.5}}\right) + A_5.\left(\frac{1}{{d_2}^{0.5}}\right) + A_6.\ H_1 + A_7.H_2 \qquad \textit{Eq.(4-5)}$$

$$\mathrm{m}_2 = A_1 + A_2.d_1 + A_3.d_2 + A_4.\left(\frac{1}{{d_1}^{0.5}}\right) + A_5.\left(\frac{1}{{d_2}^{0.5}}\right) + A_6.\left(\frac{1}{{d_1}^{2}}\right) + A_7.H_1 + A_8.H_2 \qquad \textit{Eq.(4-6)}$$

The regression coefficients values for Eq. (4-5) and Eq. (4-6) are summarized in Table 4-4.

Step 4: The elastic moduli of the surface and base layers, E_1 and E_2, are computed from the moduli ratios and the value of the resilient modulus of the subgrade soil, MR.

It is important to mention that the method described above, are valid for the range of layer moduli and thicknesses used in the development of the two dataset. The method should not be used for a pavement with a surface layer thicker than 4.0 inches because the LWD load is not able to generate a large enough stress at the top of the subgrade soil layer. The method should not be used for a pavement with a surface layer thinner than 2.0 inches. For such a pavement, linear-elastic models, such as WinJULEA, cannot accurately estimate the surface deflections because the ratio between the thickness of the surface layer and the diameter of the LWD loading plate is too small.

Table 4-4 Regression Models For The Pavement With 3.0-4.0 Inch Asphalt Layer

	To compute m_1		To compute m_2	
	Coefficient	p-value	Coefficient	p-value
A_1	43768.66	<0.0001	-918.98	0.0033
A_2	3567.54	<0.0001	-265.99	<0.0001
A_3	-13614.04	<0.0001	531.67	<0.0001
A_4	28477.22	<0.0001	-3,209.3	<0.0001
A_5	-61861.76	<0.0001	3,481	<0.0001
A_6	-57.53	<0.0001	676.13	<0.0001
A_7	45.50	<0.0001	-8.88	<0.0001
A_8	0	-	-9.91	<0.0001
R-square	0.8410		0.8902	
Root MSE	29.7		4.08	

Many multi-linear relationships between moduli ratios and deflection ratios were developed. These models were then evaluated for goodness of fit and effectiveness. The goodness of fit was represented by the coefficient of determination, R-square. The evaluation of effectiveness relied of the following:

- For a given moduli ratios, m_1 and m_2, the deflection ratios increases when the layer thicknesses, H_1 and H_2 decrease.
- For given layer thicknesses, H_1 and H_2, when the moduli ratios m_1 and m_2 increase the deflection ratios, d_1 and d_2, decrease.

Also, independent variables have been verified to be statistically significant. An independent variable is statistically significant when the p-value for its coefficient is smaller than 0.05.

Chapter 5

Conclusions

This study developed a simple set of equations to calculate the pavement layers elastic moduli directly from Light Weight Deflectometers (LWD) deflection data, for a pavement structure consisting of an asphalt concrete surface layer with thickness between 2.0 and 4.0 inches and an asphalt base layer between 4.0 and 8.0 inches. Surface deflections have been computed for this pavement structures when loaded with a typical load applied by the LWD utilizing the linear-elastic software program WinJULEA.

Two pairs of equations have been developed (one pair for the thin pavement structure and one pair for the thicker pavement structure) through multi-linear regression analysis conducted in Microsoft Excel and the SAS statistical software.

The developed equations can compute the modular ratios of the upper layers, E_1 and E_2, and the resilient modulus of the subgrade soil, MR, from the deflection data recorded by three geophones. By replacing the subgrade resilient modulus value computed directly for the outmost measured deflection into the equations that estimate the modular ratios, the elastic moduli of the upper layers, E_1 and E_2, can be derived.

This approach has two advantages:

1) The equations are suitable for the analysis of the deflection data collected by an LWD equipped with three geophones. The LWD is smaller, cheaper and easier to operate than the Falling Weight Deflectometer (FWD).
2) The equations can be easily included in the program that records the LWD deflection data. This program can be installed in the Palm Pilot device that operates the LWD. In this way, the layer moduli can be estimated at the same time the deflection test is performed; no further, separate analysis of the data is needed.

The statistical analysis suggests that the developed equations have a reasonable goodness-of-fit. The average R^2 for the equations used for thin asphalt pavement (asphalt layer thickness of 2.0 to 3.0 inches) is 0.87 and for the thicker asphalt pavement (asphalt layer thickness of 3.0 to 4.0 inches) is 0.86.

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