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FEASIBILITY OF SEISMIC TOMOGRAPHIC IMAGING

IN PAVEMENT EVALUATION

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by

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ABSTRACT

Nondestructive testing devices and backcalculation of pavement layer moduli are used to predict the pavement material characteristics and pavement response. It is of importance to achieve awareness of the limitations of these procedures. The main objectives with regard to this were to verify the accuracy of the backcalculation procedure on the basis of comparing the measured and the predicted deflections.

The primary objective of this study was to perform seismic tomographic imaging on a pavement and to conclude on its feasibility. Seismic tomography is an alternative methodology ventured to obtain the pavement material properties.

From the verification of the accuracy of the backcalculation it was realized that limitations arising due to nonlinearity maybe a cause for the mismatch in the measured and theoretical deflections.

The tomographic imaging performed in this case study yielded reasonable results. Based on this case study, it may be concluded that seismic tomographic imaging has the potential of an effective research tool.

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CHAPTER ONE

INTRODUCTION

1.1 Problem Statement

An appropriate mechanistic pavement design should be based on an appropriate theoretical model which can predict the behavior of a pavement structure. The elastic layer theory and the finite element method, as well as other approaches, have been used for this purpose. However, the elastic layer theory is generally adopted. Characterizing an existing pavement involves nondestructive testing, and backcalculation of pavement layer moduli. With the backcalculation procedure and nondestructive testing (NDT), the strains at the interfaces of different layers are eventually determined. These strains are inputs into equations which predict the remaining life of the pavement. An accurate evaluation of these properties are necessary so that the remaining pavement life can be realistically predicted. The backcalculation process, which is based on the numerical solution of the multilayer elastic problem, is not free from inaccuracies. It is important to quantify and determine the accuracy of the backcalculation process.

The most common technique used to determine pavement moduli is the deflection-based nondestructive tests. It would be of interest to investigate if any other methodology can be devised to obtain the required parameters. This study makes an attempt to explore one such alternative, seismic tomographic imaging.

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geotechnical engineers. But the pavement engineers have not given due thought to this promising field as a research tool.

1.2 Objectives

The objectives of this study are twofold. Firstly, to verify the accuracy of the backcalculation procedure. The other objective is to implement principles of tomographic imaging to a test site to determine its usefulness.

Various measured deflection data sets are employed to estimate the pavement parameters using the backcalculation procedure. The data sets used will be discussed in detail. Each of these data sets gave respectively a set of pavement layer moduli. The variation or repeatability of the moduli values for various deflection data sets of the same pavement system is an indicator of the reliability of the backcalculation methodology.

Another critical test that both methodologies have to endure is that of comparison of the measured deflections and the theoretical deflections calculated, for the same considered points within the pavement system.

1.3 Organization

In Chapter Two, the literature review of the elastic layer theory is presented. Since the Falling Weight Deflectometer was used extensively in this experiment a brief description of this is also provided.

In Chapter Three, principles of seismic tomographic imaging are described.

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In Chapter Four, the experimental set-up that was used to collect the various measured deflection data is described. Chapter Four, presents the measured deflection data and the pavement layer moduli determined using the backcalculation procedure from various data sets. The details of the characterization are also discussed.

Chapter Five contains the results of tomographic imaging.

In Chapter Six, the pavement characterizations obtained from backcalculation and tomography are compared. This chapter also includes the comparison of the measured and theoretical deflections obtained from both methodologies. Finally, Chapter Six presents an overview of the primary observations and conclusions which can be drawn from this investigation.

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CHAPTER TWO

PAVEMENT NONDESTRUCTIVE TESTING

2.1 Introduction

This chapter presents a brief overview of the elastic layer theory, the backcalculation procedure, details of the falling weight deflectometer used in the experiment and the estimation of remaining life of a pavement, all of which constitute the essence of nondestructive testing.

2.2 Elastic Layer Theory

The theory of elasticity is the fundamental procedure that has been used to calculate stresses in a continuum subjected to a load. The simplest configuration is a layer of one material. This problem was solved by Boussinesq, and is considered to be the starting point for elastic analysis of layered structures.

A flexible pavement is more realistically represented by three or more layers as shown in Figure 2.1. The assumptions made in the multi-layer elastic theory are (Yoder and Witczak, 1975):

1. The material properties of all the layers are homogeneous.
2. All the layers are of finite thickness, except for the last layer which is considered to be semi-infinite. All layers are infinite in the lateral direction (no joints or cracks in the vicinity of the load).
3. All the layers are isotropic.

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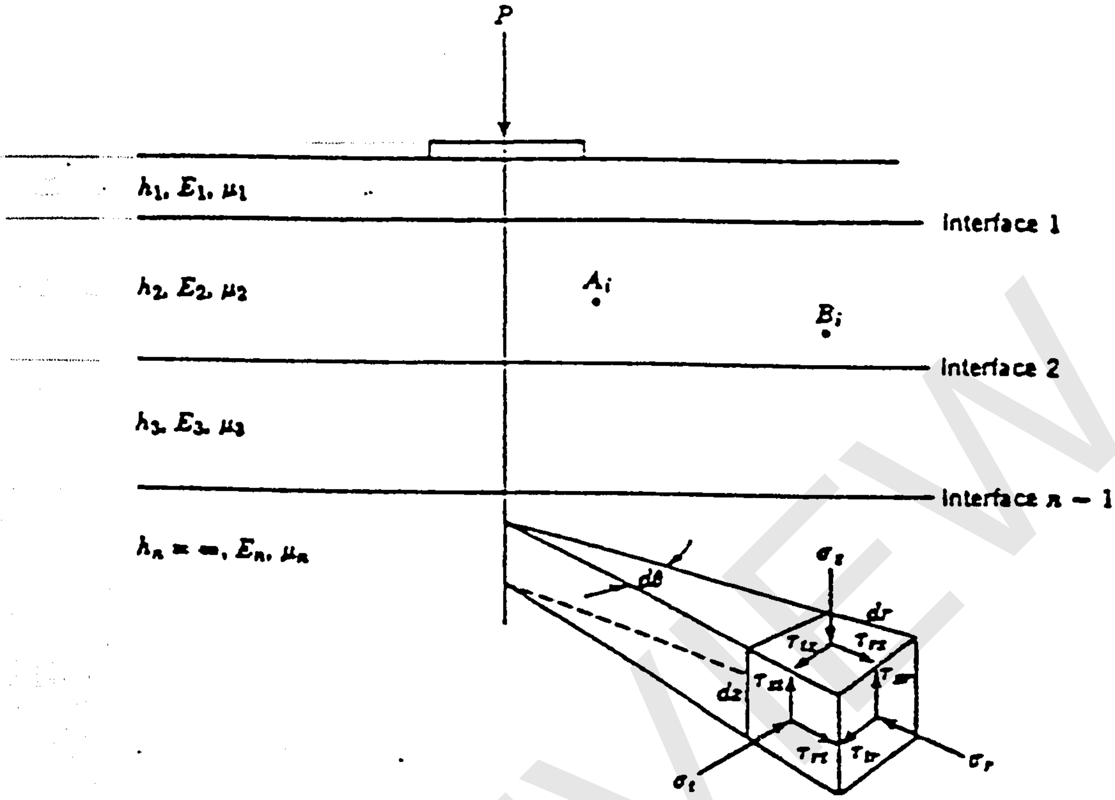
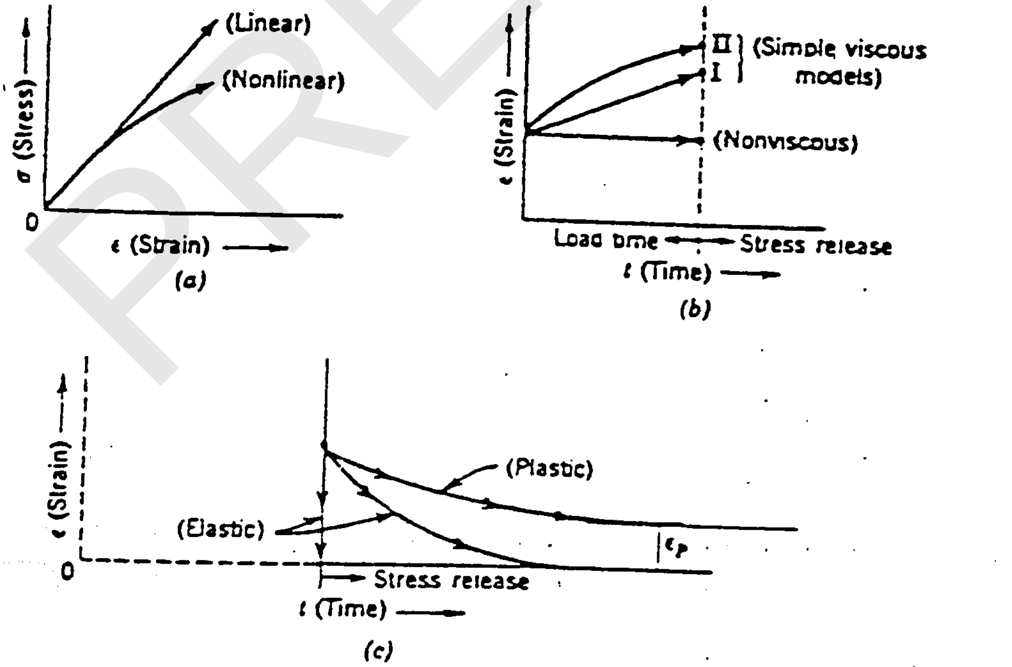


Figure 2.1 Generalized Multilayered Elastic System (from Yoder and Witczak, 1975).



(a) linearity; (b) viscous effects; (c) recoverable effects.

Figure 2.2 Typical Materials Characteristics (from Yoder and Witczak, 1975).

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4. Full friction is developed between all layers at every layer interface.
5. Surface shearing forces (frictional forces) are not present at the surface.
6. The stress solutions are characterized by two material properties for each layer, Poisson's ratio and elastic modulus.

Figure 2.1 shows an isolated element within the pavement structure to show the state of stress in a pavement material. A total of nine stress components exist. These stresses are comprised of three normal stresses (σ_z, σ_r, σ_t) acting perpendicular to the element face and six shearing stresses (τ_{rt}, τ_{tr}, τ_{zr}, τ_{rz}, τ_{tz}, τ_{zt}) acting parallel to the face.

There are limitations to the application of the elastic layer theory (Yoder and Witczak, 1975):

1. In the linear elastic theory, all materials are assumed to respond linearly over any stress range (see Figure 2.2a). Paving materials are "stress dependent," i.e, their responses are functions of their stress state.
2. In the linear elastic theory, the material response is assumed to be nonviscous (Figure 2.2b). Asphalt concrete is a complex viscoelastic material depending on time and stress states. The strains vary with the loading time for the same given load. Linear elastic theory can only approximate its properties.
3. In the linear elastic theory, the deformations are assumed to be recoverable (see Figure 2.2c). In reality, the deformations of paving materials require a long time to fully recover.

These limitations in the theory give rise to uncertainty in the accuracy of the results.

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2.3 Nondestructive Testing Device

Nondestructive structural evaluation of pavements consists of measurements of pavement surface deflection at several points. These deflections are analyzed to determine the structural adequacy of the pavement. With multilayered linear elastic theory the measured deflection basins are used to estimate insitu material characteristics of pavement layers and subsequently, rehabilitation design is performed by predicting the remaining life of the pavement.

The NDT device used in this experiment was a Falling Weight Deflectometer (FWD). The equipment is illustrated in Figure 2.3. It is a pavement loading device used to produce transient impulse forces. The load is applied to the pavement through a circular loading plate. The applied load, measured by a load cell above the loading plate, produces a corresponding deflection of the pavement structure. This deflection is measured by seismic deflection transducers placed at selected points to determine the deflection basin.

The FWD is a trailer mounted device which can be towed by any standard passenger car or van at highway speeds. The total weight of the impulse generating device and the trailer does not exceed 9 kN. The transient pulse generating device is the trailer mounted frame capable of directing different mass configurations to fall from a preset height, perpendicular to the surface. This gives the capability to produce a wide range of peak force amplitude, where peak force can be changed by varying mass and/or height.

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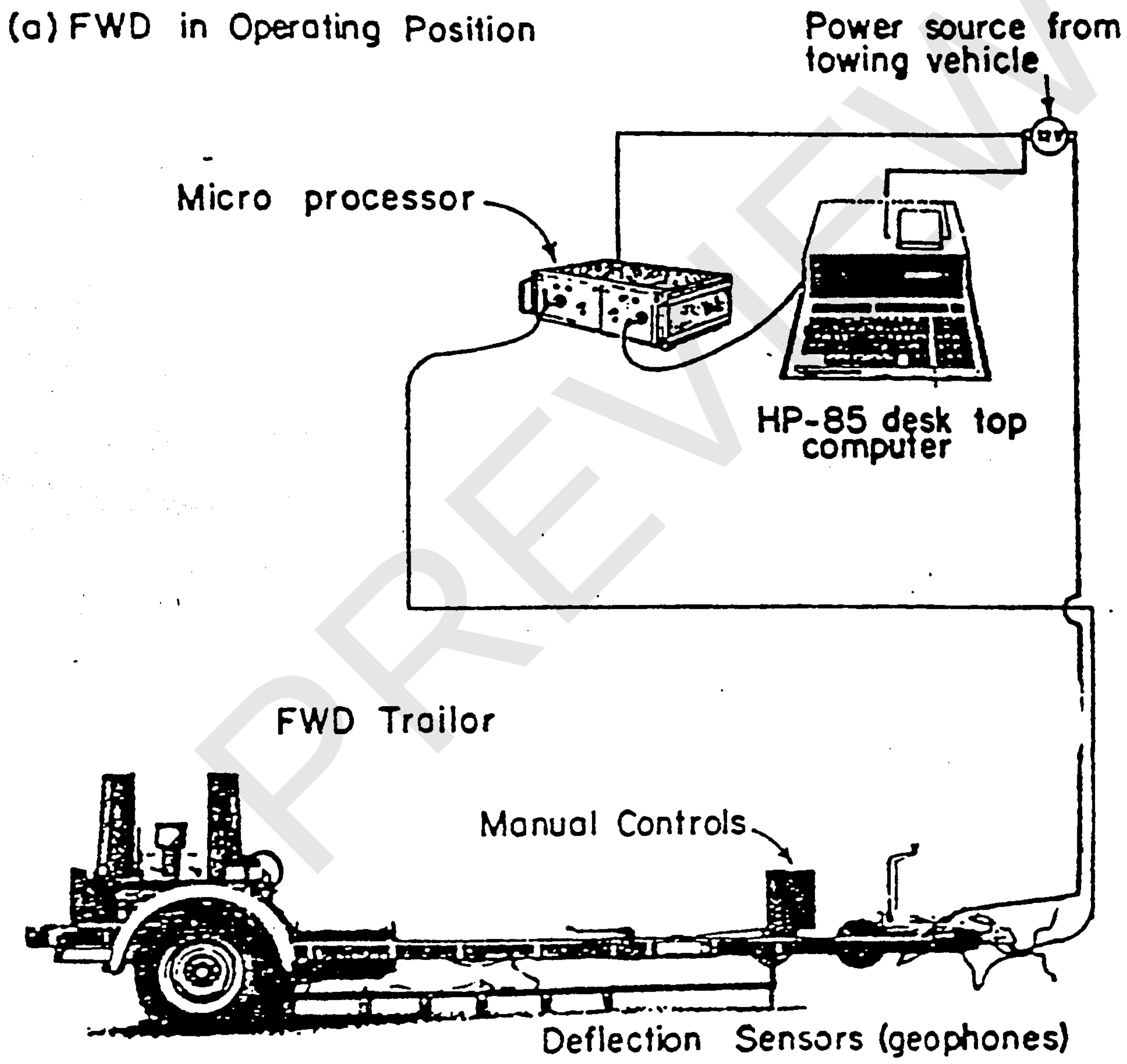

Figure 2.3 Illustration of FWD (After Ricci et al., 1985)

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2.4 Backcalculation of Pavement Layer Properties

Using the NDT data to arrive at the elastic stiffness of the pavements involves the procedure called the backcalculation of pavement properties. The main thrust in this study is to verify the backcalculation procedure, by comparing its results to the alternative approach's results. As mentioned earlier, the alternative approach that is being ventured is the tomographic imaging method.

Various computer codes have been developed to backcalculate layer moduli for pavements with three or more layers (Lytton, 1989). The typical features of these methods are illustrated in Figure 2.4.

Measured Deflections - These are the deflections that are measured with geophones and their positions from the load which caused the deflections.

Layer Thickness and Load - These give the physical features of the pavement that is tested, the load level, and the area of load application.

Seed Moduli - The initial values of the layer moduli are called seed moduli. These can either be preset or generated from the known deflections. Assumed values of Poisson's ratios are used in all methods.

Deflection Calculation - Deflections in pavements are calculated using the elastic layer theory. Various computer programs are available to perform this. One of the programs used is BISAR (Dejong et al., 1973). These codes calculate the deflections given the layer thicknesses, load, the known or predicted set of layer moduli, and the radii to the deflection sensors. The program used in this study was BISAR.

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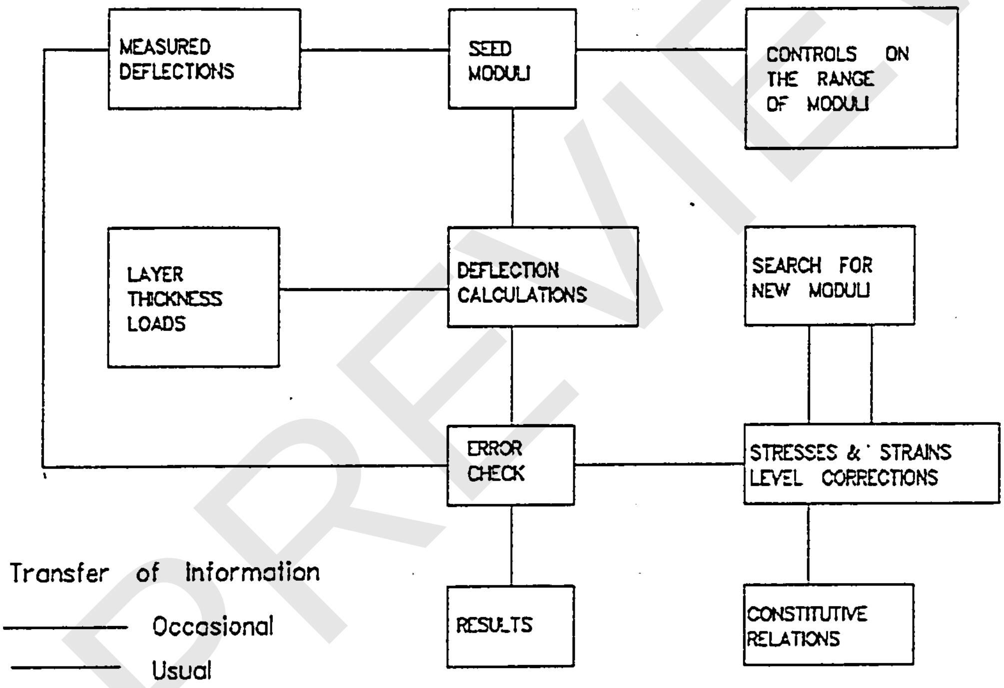

Figure 2.4 Common Features of Backcalculation (after Lytton, 1989)

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Error Check - Error checks are used to determine the convergence of results. If the error is within acceptable levels of tolerance the results are considered final. The different types of error checks are the sum of the squared differences between the measured and calculated deflections, the sum of the absolute differences and the sum of squared relative errors.

Results - These are the measured and calculated deflections, the differences and percent differences, the final set of layer moduli, and the error sums.

Constitutive Relations - These are based on linear elastic theory with no corrections for non-linearity. These relations are used in determining the moduli.

Stress and Strain Level Corrections - Using the constitutive equations for each layer and stresses or strains a new layer modulus is estimated. With this the next iteration to search for a new set of layer moduli is performed.

Search for new moduli - Various codes use different methods to achieve this. All these methods try to search for a new set of layer moduli based on the error values. This search is based on the least error values, the best fit of the measured basins and the best set of layer moduli.

Controls of the range of moduli - To achieve convergence of the iterative search toward a set of moduli that are considered to be acceptable, numerous controls are applied to direct the search away from the unwanted or unreasonable values of the moduli. A few examples for these controls are assumption of the type of pavement that is analyzed, assuming, that the

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moduli decrease with depth, another example is the assumption that subgrade modulus is constant with depth and that a rigid layer exists at a depth below the subgrade, or that a relationship exists between the modulus of the lower layers and that of the layer above it. When these assumptions are violated like when stabilized layers or thin, soft layers exist, convergence of the results are hampered.

2.5 Program BISAR and Program BISDEF

In this study the program BISAR (Dejong et al., 1973) , developed by Shell, was used to predict the pavement response (deflections, stresses, strains). This program models pavements as elastic layers. If the thickness, Young's modulus and the Poisson's ratio for each layer are known, a unique pavement response can be predicted. The program BISDEF (Bush, 1980), developed by the US Army Corps of Engineers (WES) is one of the programs which performs backcalculation of moduli from surface deflections. This program was used in this study. In our study besides surface deflections even embedded deflections within the pavement systems were used for the backcalculation of the layer moduli.

When using this kind of layered linear elastic model to match the deflections obtained from the NDT devices the following problems exist (Uddin and McCullough, 1989)

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1. The pavement response is measured using a dynamic test load. This loading is different from the magnitude and loading mode of the design wheel load. Therefore, it does not simulate typical pavement loadings.
2. The measured response is a dynamic deflection basin but layered elastic theory is a static analysis, which predicts static deflections for static loads.
3. The structural response calculated for a structure with known properties is always unique, but non-unique combinations of moduli of the pavement layers may yield the same or similar measured response.

2.6 Computation of Allowable Passes, Required Overlay Thicknesses

An airport pavement was used in this study. For the estimation of the pavement response the loading of a Boeing-727 aircraft is adopted. The details of the loading characteristics are discussed in Alexander et al (1989). A computer program AIRPAVE was used to estimate the critical strains, allowable passes and required overlay thicknesses. This program has incorporated the BISAR subroutine earlier reviewed. AIRPAVE determines the limiting values of stress and strain, which are used to estimate the allowable passes using the following relationships:

$$Allowable\ Strain_{AC} = 10^{\frac{-(N+2.665\log_{10}(\frac{E_{AC}}{14.22})+0.392)}{5}} \quad (2.1)$$

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