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Co-variance matrix adaptation evolution strategy for pavement backcalculation

Kasthurirangan Gopalakrishnan [a,*], Anshu Manik [b]

[a] Dept. of Civil, Construction, & Environmental Engineering, Iowa State University, 354 Town Engineering Building, Ames, IA 50011, USA
[b] Wolfram Research Inc., 100 Trade Center Dr., Champaign, IL, 61820, USA

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ABSTRACT

The falling weight deflectometer (FWD) is the foremost and widely accepted tool for characterizing the deflection basins of pavements in a non-destructive manner. The FWD pavement deflection data are used to determine the in situ mechanical properties (elastic moduli) of the pavement layers through inverse analysis, a process commonly referred to as backcalculation (B/C). Several B/C methodologies have been proposed over the years, each with individual strengths and weaknesses. Hybrid methods (combining two methods or more) are recently proposed for overcoming problems posed by stand-alone methods, while extracting and compounding the benefits that are individually offered. This paper proposes a novel hybrid strategy that integrates co-variance matrix Adaptation (CMA) evolution strategy, Finite element (FE) modeling with neural networks (NN) non-linear mapping for backcalculation of non-linear, stress dependent pavement layer moduli. The resulting strategy, referred as CMANIA (CMA with neural networks for inverse analysis) is applied for asphalt pavement moduli backcalculation and is compared with a conventional B/C approach. Results demonstrate the superiority of this method in terms of higher accuracy, achieving nearer to global solutions, better computational speed, and robustness in predicting the pavement layer moduli over the conventional methods.

1. Introduction

Growing infrastructural needs reinforced by sustainable vision is driving engineers to persistently search for judiciously selected resources; cautious planning and green execution of projects with stricter quality control and quality assurance measures; robust maintenance strategies and an incessant learning and up-gradation of our approaches while dealing with such issues. Considering the length, structure and the load carrying capacity of modern world road infrastructure and the speed with which Nations are investing in such infrastructure, highway engineers are always in need of flexible, speedy, robust and reliable methods of determining the physical condition of the pavements or pavement sections under examination. The introduction of mechanistic design methods, such as the recently released Mechanistic Empirical Pavement Design Guide (MEPDG) [1], requires that fundamental pavement material properties such as resilient modulus be measured under conditions that replicates field environment. Efficient and effective usage of the pavement materials in regards to the strength and stiffness forms the core idea of such a design procedure.

Amongst the two significant non-destructive (NDT) methods viz. deflection basin methods and surface wave method, the former is a subject of discussion of this paper. The falling weight deflectometer (FWD) is the foremost and widely accepted tool for characterizing the deflection basins of pavements. The FWD pavement deflection data are used to determine the in situ mechanical properties (elastic moduli) of the pavement layers through inverse analysis, a process commonly referred to as backcalculation (B/C).

Typically, the process of backcalculation involves comparison of FWD measured deflections with computed deflections (using a pavement response model) through an iterative optimization procedure to determine the representative pavement layer moduli which could have produced the measured FWD deflections. The inherent nature of pavement structure amalgamated with heterogeneous nature of pavement component layers and their responses to traffic, environmental and interaction loads makes the inverse modeling very challenging.

Several B/C methodologies have been proposed over the years to resolve these and associated computational problems, each with individual strengths and weaknesses. Hybrid methods (combining two methods or more) are recently proposed for overcoming problems posed by stand-alone methods, while extracting and compounding the benefits that are individually offered. This paper introduces one such novel hybrid technique (CMANIA) that integrates co-variance matrix adaptation (CMA) evolution strategy, finite element (FE) modeling with neural networks (NN) non-linear mapping for real-time non-destructive evaluation and inverse modeling of pavement systems. This paper discusses the concept,

* Corresponding author. Tel.: +1 515 294 3044; fax: +1 515 294 8216.
E-mail addresses: rangan@iastate.edu (K. Gopalakrishnan), anshum@wolfram.com (A. Manik).

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application feasibility, comparisons with existing conventional approaches and validation of CMANIA for the B/C of pavement layer moduli.

2. Background

The need for speedy evaluation of the structural properties of highway pavements on a road network-wide basis has led to the widespread use of NDT equipments. The most common form of NDT employed worldwide by road engineers is surface-deflection based procedure. It consists of surface deflection basin measurements and pavement layer properties back-calculation [21]. NDTs for measuring pavement surface deflections (PSd) (for evaluating flexible pavement structure and rigid pavement load transfer) and B/C of pavement layer properties are strongly recommended and/or incorporated in the design, maintenance and rehabilitation procedures and strategies by several transportation related organizations across the world. These include the American association of state highways and transportation officials (AASHTO) [1], the European countries [47], the Australian Road research board (ARRB) [10,50], New Zealand transport agency [72], Peoples' republic of China [76], National highways authority of India (NHAI) [59], etc.

2.1. Falling weight deflectometer

FWD is the main, simple and very useful non-destructive tool available to most Departments of Transportation (DOTs) around the world for diagnosing structural deficiencies and for designing pavement strengthening requirements [63]. The advantage of an impact load response measuring device over a steady state deflection measuring device is that it is simpler, quicker, the impact load can be easily varied and it more accurately simulates the transient loading of traffic. During the last two decades, FWD and the measurements made using this type of NDT equipment have gained their own place in routine pavement management practices in many countries [49].

2.1.1. Working principle

A FWD test is performed by applying an impulse (dynamic) load to the pavement surface by dropping a free falling weight onto a circular metal plate with a pre-determined force. Sensors placed around the plate and in straight line radiating from the center of the load plate record the resulting PSd's. The experimental data is usually summarized as a deflection basin that is constructed from the peak deflections recorded at each of the measurement locations [49,54]. A picture of the FWD equipment attached to a van is shown in Fig. 1.

Accurate measurement of deflection data with the FWD forms an integral part and plays a decisive role in estimating the structural condition of a pavement. In addition to the variations in the pavement cross-section, traffic, environmental factors, pavement discontinuities and variability in the pavement structure significantly affect the pavement deflections [19]. Frequent calibration, maintenance, adoption of proper and systematic testing procedures and operator training are required for accurate estimation of the deflection basins, while minimizing the deflection measurement errors [40].

2.1.2. State of practice

The FWD can either be mounted in a vehicle or on a trailer and is equipped with a weight and several velocity transducer sensors. To perform a test, the vehicle is stopped and the loading plate (weight) is positioned over the desired location. The sensors are then lowered to the pavement surface and the weight is dropped. Multiple tests can be performed on the same location using different weight drop heights [8]. Results are communicated through a suitable data acquisition system. A series of numbers describing the deflection basin shape are produced. Although these numbers are self-descriptive, but they are often represented in a form of a single indices like FWD AREA parameter [73].

Fig. 1. Falling weight deflectometer (FWD) equipment.

2.2. Pavement moduli backcalculation problem

The basic objective of FWD evaluation is to estimate the in situ layer moduli when the deflection profile is given – this is the called the inverse modeling of pavement systems or the backcalculation (B/C) problem [64]. This problem is also called as parameter identification problem and involves an optimization process often performed to obtain the inverse mapping of a known relation. B/C in pavement systems involves a process of comparing, calibrating and synthesizing the measured deflections with the computed ones. This involves using an equivalent pavement response model subjected to an iterative process, in which the deflection values are computed using a set of seed moduli. Subsequently, the iterations are continued until a proximal and 'tolerable' match (converging) between measured and computed deflection values is established. This pavement model is then run with a variety of different 'trial' layer properties until a set of properties is found which causes the measured deflection basin to be reproduced [48,54,74,75]. Lytton [48] provides a historical review of FWD B/C involving empirical methods and computer programs, while Goktepe et al. [23] provide a review of the advances made in B/C procedures.

The problem of B/C of layered moduli is a complex one and accurate and quick estimation of the moduli is indeed a challenge. Over the years, various approaches have evolved, which include closed form solutions [25], database search [6,16], optimization techniques [12,34,76], and regression equations [5,57] amongst others. A significant amount of research has also been focused on algorithms to interpret deflection data from specific structures [52].

Broadly speaking, several static, dynamic, and adaptive techniques [13,21,24,39,54,62,66,75] have been proposed for backcalculation of flexible pavement layer moduli such as the least-squares (parameter identification), database search, soft computing techniques such as neural networks (NNs), neuro-fuzzy systems, and Genetic Algorithms (GAs), Most of the commercial backcalculation programs currently employ some type of gradient search technique to find the set of layer properties that produces the best match to the experimental deflection basin [23].