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Classification of measures from deflection tests by means of fuzzy clustering techniques

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HIGHLIGHTS

- We applied a clustering technique to classify real-time HWD data in two clusters.
- The classification was evaluated by membership degrees.
- The number of clusters, however, can be expanded to classify new observations.
- The procedure permits to know the characteristic of the pavement in real time.
- It is possible to exclude one or more geophones when there are problems.

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ABSTRACT

As everybody knows, non-destructive tests carried out with the Heavy (or Falling) Weight Deflectometer equipment permit to identify the mechanical properties of the layers constituting a road or an airport pavement.

The ordinary activity generally causes at least two issues: (a) impossibility to anticipate the stiffness of the pavement analyzed during the trial; (b) probable mistakes induced by punctual degradations. In the latter case it would be more appropriate to discard the reading of one or more geophones for a correct determination of the modules.

In order to overcome the above limitations, we propose a procedure based on a fuzzy clustering technique that enables the classification of the deflections in real time, reducing the number of drops (generally equal to 3), with no need for traditional back-analysis. Any uncertainty of the result achieved is quantified by the fuzzy membership degree for which the analyst has an objective measure of the representativeness of the data detected.

1. Introduction

The structural characteristics of an airport pavement can be derived through Non-Destructive Testing (NDT) by means of equipments that, with simple deflection measures of the pavement surface, return the main mechanical properties of individual layers. For example, the Falling Weight Deflectometer (FWD), or its heavier version called Heavy Weight Deflectometer (HWD), comprises, as everybody knows, a mass that is dropped from a certain height (both chosen according to the load to be simulated) on a plate, which, through a system of springs, transmits the received pulse to another plate (whose diameter is 300 mm) positioned on the pavement surface. The resulting deformation surrounding the impact point is measured by a series of geophones (generally from 7 to 15), positioned at some distances from the axis of the plate. Deflection bowl, air and pavement temperatures, Poisson's ratio, load and thickness of the layers (obtained by core sampling or GPR analysis) constitute the input of the system while the output is represented by the layers moduli, computed through a back-calculation procedure.

1.1. Background

In the last years, scientific research has produced different approaches to this framework, from the most simple and inaccurate methodologies (linear elastic theory and method of equivalent thickness) to the most complicated solutions (as, for example, finite elements), essential if we want to represent in detail the dynamic phenomena of a deflection test. In this regard, Uzan [1] and Appea [2] have presented a dynamic linear model, well correlated with the results of some ordinary laboratory tests which were able to deduce easily the mechanical properties of materials. Chang et al. [3], similarly to results achieved by Liang and Zhu [4], have

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developed a program to interpret the steady-state deflection measurements, obtaining better results than similar static methods published so far. Lately, the physical phenomenon, which is the basis of the deflection test, has been refined with greater precision, also for the development achieved by modern computers. With this aim, Westover and Guzina [5] have schematized the reflection and refraction of the load waves and the visco-elastic response of the pavement by means of a pre-processing procedure in the frequency domain based on Fourier Transform and able to be implemented in the elasto-static patterns of traditional back-analysis.

Further variations on back-calculation procedures have been followed by numerous authors, including Stubstad et al. [6], that have devised a technique of forward-calculation directly in closed form for the estimation of the modules, rather than through iterations.

As told in advance, more rudimentary methods, such as the equivalent thickness one (method of equivalent thickness), continue to meet with great success because of their simplicity and speed of calculation and have been reviewed and refined with a certain continuity [7,8].

The theories relating to the System Information were also applied to the deflectometer tests. This research area studies phenomena characterized by the knowledge of inputs and outputs when it is not known the transfer function that, therefore, must be hypothesized and later validated. Seo et al. [9] have focused on the control of the differences between the measured output of the real system compared to the simulated one, accounting for this difference with an error function minimized by an optimization procedure.

In any case, both the static and dynamic methods, in their various forms, produce very long calculation times. In the recent past, this problem has been dealt with approaches based on regression equations [10,11] or on database back-calculation method [12,13]. These proposals, unfortunately, cannot easily be generalized and are, therefore, hardly extensible to cases different from those used to calibrate them.

Surveys with the device FWD/HWD produce a lot of data concerning deflection bowl, temperatures, thickness of the layers, etc. The rapidity of the test permits the exam of several sections in a reasonably short time. This leads to manage a post processing phase with data set of large dimensions that should be treated with advanced analytical techniques in order to extract useful information and discard those irrelevant but, above all, to predict the most important variables.

Tools to resolve these issues can reasonably be based on artificial intelligence [14–19] or pattern recognition techniques, developed for the treatment of large quantities of data recorded by digital instruments and applied to sort, classify or extract data useful for understanding the investigated problem. The main advantages regard, not only the comprehension of the phenomenon, but also the removal of irrelevant dimensions or reduction of data acquisition cost [20–24]. Saltan et al. [25], for example, have proposed a fuzzy model that allows one to predict the dynamic loads of non-linear type with great rapidity. Subsequently, the same authors have applied data mining techniques to traditional back analysis to estimate the data of deflection from a FWD.

1.2. The present research

The purpose of this research is the proposal of an expeditious procedure capable to be applied during HWD (or FWD) tests that, starting from the knowledge of the information regarding the deflections, predicts the mechanical condition of the pavement layers.

The choice of an appropriate methodology for the treatment of data must take into account the number of the input variables, as well as possible correlations. The uncertain nature of the phenomenon and the need to know the results in a short time, have directed the choice towards the Fuzzy C-Means (FCM) technique. This methodology not only classifies all the data surveyed in a proper way, but permits to evaluate new observations without any back-calculation procedure. The model must, of course, be trained with a number of observations in which the modules are known. Subsequently, the new observations can be introduced without prior knowledge of the output data that, therefore, will be predicted, at least within the range of a certain class. These techniques have already been applied to the civil engineering tests and have been particularly convincing [26–30].

Our tool could be useful for identifying the most critical sections to be further investigated and, at the same time, to survey large areas in a faster way [31–35].

This study therefore has the following objectives:

- Organization of a training data set, including measures of the deflection and the moduli taken by ordinary back-calculation procedures. This step is required to identify some clusters around which the new observations will be located.
- Identification of all new stations (just measures of the deflection) to one of the clusters identified in the previous phase, without using the ordinary back-analysis to derive moduli and by using a smaller number of drops.
- Quantification of the uncertainty of the result by determining the membership degree to the clusters.

In the present paper, we will describe the potential offered by non-destructive tests for the evaluation of the structural behavior of a pavement, focusing in particular on the HWD test. So, our paper will report a brief theoretical overview concerning the cluster analysis and, especially, its fuzzy version, particularly suitable to express uncertainties regarding the variables involved. Finally, we will evaluate the results, discussing meaning, limitations and opportunities that this procedure can offer.

2. Method

The structural behavior of an existing pavement, calculated with any analytical scheme (rheological models more or less complex, finite element), must provide a proper physical and mechanical characterization which may occur in laboratory or on site. In the latter case, it probably does not reach very high accuracy but has the advantage that the pavement may be inspected in a number of points with great rapidity and without being destroyed. The Falling (or Heavy) Weight Deflectometer, in particular, produces a dynamic impulse load that simulates a moving wheel load. This study has been carried out by an HWD Dynatest 8082 (Fig. 1), with a loading range (30–240 kN), with 9 geophones placed at a distance from the axis of loading, respectively of 0, 200, 300, 450, 600, 900, 1200, 1500 and 1800 mm and a series of thermometers for measuring the air and pavement temperatures (superficial and internal).

Starting by the deflection data, combined with layer thickness and air and pavement temperatures, we have easily obtained the "in situ" dynamic E-moduli of all the layers at the reference temperature of 25 °C by means of the Elmod® software. For each test station, 3 drops were performed with height respectively equal to 50 mm (only in order to stabilize the measure), 390 mm and 390 mm. The load plate is a conventional type "segmented", with a diameter of 300 mm, so as to ensure a uniform distribution of the tensions.

The deflections have been measured with an absolute accuracy of more than ±2 mm and with a resolution equal to 0.1 mm. The levels of the applied load have been recorded with an accuracy better than ±0.3 kN; for this parameter, the resolution varies from 0.03 to 0.2 kN in relation to the size of the applied load. The air temperature has been measured by the integrated thermometer, characterized by an accuracy of ±0.4 °C and a resolution of 0.1 °C, while for the measurement of the temperature of all the asphalt layers a digital thermometer, of accuracy ±0.2 °C and a resolution of 0.1 °C, has been used.

The survey has covered 24 stations, each consisting of three drops and in which we have derived the modules of the pavement layers. Subsequently, the data collected have been divided into two data sets: the first, composed of 18 observations, contains as input variables the load, the height of fall, the thicknesses of the various layers, the air and pavement temperatures and, of course, the deflection basin. The output is represented by the modulus of the asphalt layer.