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Back-calculation of elastic modulus of soil and subgrade from portable falling weight deflectometer measurements

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ABSTRACT

In the field of nondestructive testing of pavement, the portable deflectometer devices have gained, in the recent years, a wide use for in situ assessment of elastic properties of soils, subgrade and pavement foundations. However, if the use of the elasto-static model based on the Boussinesq's theory does not constitute a shortcoming in the back-calculation procedure of homogenous elastic modulus, questions have been arose about the reliability and accuracy of the peak value method commonly used to extract the static stiffness of soils and subgrade from the dynamic transient data. This paper deals with the use of minimization technique, based on least square algorithm as an alternative method for data analysis and soil elastic stiffness identification. Details of the mathematical basis, the implementation and different steps for elastic modulus back calculation, are presented. In this method, an equivalent spring-mass-dashpot system, where the complex dynamic soil behavior is reduced to a viscoelastic one-dimensional wave propagation problem, is used for modeling the loading plate/soil system. The comparative study shows the suitability and the accuracy of the minimization method for soil elastic stiffness identification and elastic modulus back calculation.

1. Introduction

Since the mechanistic-empirical methods have been widely adopted in pavement design procedures, the nondestructive testing techniques (NDT) have seen an increasing interest and acceptance from pavement managers and engineers. Because they provide parameters that are useful for material optimization and pavement deterioration assessment.

Nowadays, the most promising devices are based on the application of dynamic loads using vibratory or impulse sources, and the measurement of the resulting surface deflection or the phase difference between the motions recorded at various receivers. Among the deflection based devices, the falling weight deflectometer (FWD) is the most widely used and, actually, is considered as a standard test for pavement evaluation [1,2]. However, despite of many attempts and research works, it is still not preconized to be directly used on soil and subgrade for in situ assessment of the material properties [3]. This is due to many reasons related to the accessibility for pavement under construction, to the unevenness of the surface which leads to inaccurate deflection measurement during the test [4,5] and to the weak cohesive property of soils and subgrade that makes the FWD back-calculation procedure not appropriate. To overcome this lack, the portable deflectometer devices is found to be a best alternative. Different types of devices have been developed in the world [3] (e.g., LWD PRIMA 100 of Carl Bro, PFWD of Dynatest, GDP of Zorn) and, over the years, they have experienced increasing popularity due to their light weight, quick measurements and high performance, compared to the conventional static tests (e.g., static plate test, CBR test and Benkalman beam). Publications dealing with their performance show that they can constitute a useful tool for the quality control and quality assurance (QC/QA) of newly constructed pavement foundations [6–9]. However, due to their simple concept (portable deflectometer devices use only central sensors such as geophone and accelerometer to measure deflection under the loading plate), they can only provide an evaluation of the homogeneous elastic modulus of layered media. Therefore, the half-space theory, where the soil is assumed to be homogenous, isotopic and linear elastic half-space, is often used in back calculation procedure. Furthermore, the estimation of the static stiffness is obtained by considering only the maximum values of the load and deflection. This is the so called peak value method.

Recently, many authors shown that this method leads to inaccurate estimation of the static stiffness. Hoffman et al. [10] demonstrated theoretically that the peak values method leads to significant systematic errors. To overcome this problem, they

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adopted a spectral analysis approach. By assuming that the soil structure responds as a linear single degree of freedom (SDOF) system, they extrapolated the dynamic stiffness at zero frequency that refers to the static stiffness, by fitting the theoretical frequency response function (FRF) (mobility) curve of the SDOF system to the experimental mobility data obtained by performing the Fourier transform on the time dependent data. Ruta et al. [11], showed also, on the basis of the analytical solution of a half-space under impulse load, that erroneous estimation of static stiffness can be made when using the peak value method. In order to extract the static stiffness from the dynamic transient data, they used the static flexibility which is defined as the ratio between the total displacement and the total load (impulsion) over a certain range of time. More recently, Rhayma et al. [12] developed specific diagnostic devices to analyze the behavior of railway tracks.

The aim of the present work is to assess the limitation and the reliability of the peak value method for field data interpretation and to develop an accurate, efficient and easily implementable method for soil stiffness identification. A minimization technique, using least square algorithm is used. In this method the loading plate/soil system is represented by a SDOF system, where the soil is assumed to be linearly visco-elastic [13–15].

2. Light dynaplaque

The portable deflectometer device used in this study is developed and manufactured by Rincent BTP Company. It is a handhold device that can be used easily by only one operator. It includes two parts as shown in Fig. 1. The electronic part consists of a National Instrument USB NIDaq acquisition card, a load cell, a velocity transducer (geophone) and a lap-top. The mechanical part includes, mainly, a 30 cm diameter loading plate, a sliding drop weight (10 or 16 kg), a guide rod and cylindrical shock absorbers made of rubber.

Fig. 1. Portable deflectometer device.

The operation mode of the device is simple. As the sliding drop weight is released, it strikes the cylindrical shock absorbers so that an impulse load of 5–25 ms duration with a maximum force ranging up to 35 kN, is transferred through the loading plate into the ground. The load and the motion at the center point on the surface of pavement are simultaneously monitored using a load and a velocity transducer, respectively. During the tests, two filtered digitalization channels connected to the sensors are used for data acquisition and a 10 kHz sampling frequency is chosen. This allows acquiring 4096 samples during the entire time acquisition of 410 ms. A typical time history of a recorded signals that we can visualize on the lap-top, is illustrated in Fig. 2.

3. Data interpretation method and back calculation procedure

As for many portable deflectometer devices, although the test is dynamic in nature, the elastostatic model, based on the Boussinesq's theory [16], is used in back-calculation procedure. Therefore, for a distributed load on a circular area of the free surface of a homogenous, isotropic and linear elastic half-space, the elastic modulus can be obtained as follows [17,18]:

$$E = \frac{(1 - \nu^2)}{\beta a} k \tag{1}$$

where ν is Poisson's ratio, a is the radius of the loading plate, β is the shape factor depending on the stress distribution under the loading plate ($\beta = \pi/2$, 2 and $3\pi/2$ for uniform, inverse parabolic and parabolic stresses distribution, respectively), and k is the elastic stiffness of the loading plate/half-space system, often referred to as the soil stiffness. In practice, as the loading plate is considered stiffer compared to the soil, an inverse parabolic pressure distribution is commonly used for portable falling weight deflectometer data interpretation and elastic properties evaluation. It is of the form:

$$p(r) = \frac{p_0}{\sqrt{1 - \frac{r^2}{a^2}}} \tag{2}$$

where $r \in [0, a]$ is the distance from the axis to any point in the circular loading area and p_0 is the contact pressure at the center point. This form of distribution gives rise of a uniform normal displacement under the loading plate and therefore a stress concentration at the edge Fig. 3). However, it is worth noting that it remains a simplification of the real contact pressure distribution that would appear in the field, which is highly complex and depends on device parameters, load magnitude and soil profile and properties [19,20]. Besides, we can notice easily, that the main problem in the back-calculation procedure is how to extract the elastic stiffness from the time dependent data. From the static plate tests, the elastic stiffness k is simply defined as:

$$k = \frac{P}{\delta} \tag{3}$$

where P is the applied load given by $P = 2\pi \int_0^a p(r)dr$ and δ is the induced displacement at the center point or the average of the measured displacements at three points under the loading plate. However, in the case of a dynamic plate tests (e.g., PFWD), the dynamic response of the ground to the impact loading is affected by the inertia and the damping properties of the media, that must be taken into account in order to identify, accurately, the elastic properties, namely, the elastic stiffness k, from transient data. The method proposed here consists of two steps. The first step aims to identify the elastic stiffness k. By assuming that the behavior of the rigid loading plate/soil system is comparable to that of a mass – spring – damper system Fig. 3), its dynamic equilibrium is governed by the equation: