Engineering Structures 100 (2015) 201–211

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Identification of pavement elastic moduli by means of impact test

P. Ruta *, B. Krawczyk, A. Szydło

Faculty of Civil Engineering, Wrocław University of Technology, 50-370 Wrocław, Wyb. Wyspianskiego 27, Poland

ARTICLE INFO

Article history:
Received 9 March 2015
Revised 22 May 2015
Accepted 27 May 2015
Available online 20 June 2015

Keywords:
Multi-layer elastic model
Pavement
Impact test
Falling weight deflectometer (FWD)
Inverse problem
Identification of model parameters

ABSTRACT

The practically important problem of identifying airport and road pavement model parameters by means of the falling weight deflectometer (FWD) is solved in this paper. The loads exerted by FWD have a momentary dynamic (impact) character, whereas the current computational pavement models (commonly used in practice) are static models. Dynamic models are used marginally due to their complicated mathematical description. As a result, in practice static model parameters (elastic moduli) are identified on the basis of displacements determined under a dynamic load (a force impulse), which creates an obvious methodological conflict. This paper presents a method of identifying the parameters of airport and road pavement models (in the form of multi-layered elastic half-spaces) on the basis of dynamic impulse test results, using a method of transforming the dynamic displacements into their static substitutes (i.e. the displacements which would be determined by a hypothetical static test). The presented solution makes it possible to identify model parameters for any shape of the distribution of the load (under the loading plate), approximated by a series of Legendre polynomials. The algorithm was subjected to simulation tests in order to determine the influence of the limited accuracy of the displacements yielded by the FWD test on the values of the identified parameters (elastic moduli). For this purpose randomly generated errors were added to the theoretically calculated displacements. The proposed method has been experimentally validated on a newly built flexible-pavement road section, by comparing the results yielded by it with the results of direct static measurements by means of the Benkelman beam. The results obtained by the proposed method were also compared with the currently most commonly used method which wrongly assumes that the static flexibility of a tested system can be approximated with a ratio of the maximum displacement to the maximum load, measured in the impact FWD test.

1. Introduction

This paper deals with the identification of the parameters of road and airport pavement models, using vertical pavement displacements produced and registered by means of a falling weight deflectometer (FWD). The measurement of vertical displacements by means of FWD is undoubtedly the most effective (owing to the short measurement time) nondestructive test. In current design practice and in FWD tests, the dynamic character of neither the load nor the system response to the values of the pavement model parameters being identified is taken into account. It has been empirically [1,2,3] and theoretically [3] shown that depending on the way (static/dynamic) of loading, there are significant differences in the determined vertical displacements of the structure and so it becomes necessary to develop a method of transforming the displacements obtained from the dynamic test into their static substitutes to be used in much analytically simpler pavement structure models. It has been the practice so far in FWD road and airport pavement tests to record pavement boundary surface deflection measurements in the form of a discrete set of displacements (a deflection basin). The displacements are then used in the procedures for identifying model parameters (elastic moduli), allowing for further assessment of pavement condition and bearing capacity. There are also other measures (parameters) introduced, among others, by Butler and Kennedy [4], consisting in deflection basin shape-measurements (Surface Curvature Index, Base Curvature Index et al.). Both the BCI and SCI parameters (universally used in pavement diagnostics), however, are not directly linked to moduli identification and give, according to authors opinion, simplified “picture” of the pavement condition in comparison to full identification. Thus, they are not discussed in the article.

The dynamic loads exerted on the surface by FWD have an impact character and the registered pavement displacements represent the dynamic response to the load. In design practice, however, static pavement models in the form of layered elastic half-spaces are most often used. This means that it is the static

* Corresponding author. Tel.: +48 71 320 48 50.
E-mail address: piotr.ruta@pwr.edu.pl (P. Ruta).

http://dx.doi.org/10.1016/j.engstruct.2015.05.038
0141-0296/

model parameters (moduli) which are identified on the basis of the deflection basin obtained under a dynamic load (a force impulse). It is worth notice, that in reality we deal with a visco-elastic model (in case of the flexible pavements), which mechanical properties are time-dependent. Short impulse load however, ensures that the pavement response is rather elastic than visco-elastic. Analysis of the simplified elastic model do not generate, according to authors experience, any significant errors in that matter. Separate tests at different load levels have been carried out by authors, showing linear load magnitude – vertical deflection dependence. According to the research results identification of the elastic parameters on the basis of falling weight test (at short impulse load) is justified.

The theoretical basis for the method were created by Langer and Ruta [5] in the early 1990s. But because the above authors had no access to proper measuring apparatus the theory could not be verified in practice. Only as late as 2003, results of comparative studies of the subgrade with the use of a dynamic lightweight plate and static load plate [3] (with only the displacements directly under the loading plate, in the axis of loading, being registered) were reported. In paper Ruta and Szydło [3] it was shown that the simplified method of identifying subgrade moduli, based solely on the maximum displacement values registered in the dynamic impact test, yielded results which sometimes carried considerable errors. It was also shown that the magnitude of these errors is significantly affected by the duration of the loading impulse. In [3] also the moduli identified through the static test and the impact test, taking into account the load time history and the system response, were compared and good agreement between the respective results was obtained.

New possibilities opened up with the use of FWD since this device enabled the simultaneous registration of displacements in many measuring points, i.e. the registration of the deflection basin, which is essential for the identification of multilayer model parameters.

The assessment of the effect of the FWD test load dynamic character on the pavement model parameters being identified is still a current problem. FEM based research into this problem is being conducted in South Korea [6] and France [7,8]. Interesting examples of analytic solution of dynamics inverse problem have been presented in the papers: Al-Khoury et al. [9–11]. The solution presented below has not been reported before in the literature on the subject.

This paper presents a method of identifying the parameters of road and airport pavement models in the form of a multilayer elastic half-space, using the transformation of dynamic displacements into static substitutes (see [3,5]). The model parameters being identified are the elasticity moduli E_i of the layers. The other parameters, such as the Poisson ratios ν_i of the layers and the latter's thicknesses h_i are assumed to be known. Identified elastic moduli (of the bituminous layers) can be compared to stiffness modulus which is stress to strain ratio (in uniaxial stress) at given loading time (t) and temperature (T). Such definition has been already presented by Van der Poel [12]. In case of FWD tests, there is a short impulse load, that prevents "visco" effects to occur (temperature is still relevant in pavement moduli identification). In the paper, by elastic modulus identification, one should understand as stiffness moduli identification at a short loading time and in-situ temperature.

Using the proposed method it is possible to identify the parameters for any distribution of the function of loads (the forces of interaction between the FWD loading plate and the tested system surface). The algorithm was subjected to simulation tests to check the effect of the limited accuracy of the displacements determined in the impact test on the identified values of the moduli. The simulation consisted in adding randomly generated errors to the theoretically calculated (for the assigned known moduli) displacements and using the values encumbered with the errors as the "experimental" data for the identification of the elasticity moduli E_i of the layers. The values obtained from the tests were subjected to statistical processing to determine the statistics of the identified moduli.

Also identification results obtained on the basis of in situ FWD tests and tests with static loads applied by means of the Benkelman beam are reported in this paper. The tests were carried out on a newly built section of a road with a flexible pavement.

The results of the simulation and in situ tests have confirmed the suitability of the proposed method for the identification of the parameters of multilayered road and airport pavement models.

2. Problem formulation

The problem considered here is the identification of the elasticity moduli of a layered elastic system (pavement) on the basis of impact test results. The impact test is carried out using the falling weight deflectometer (FWD). FWD is a device used for measuring the vertical displacements of a pavement structure caused by the load generated by a free falling mass. FWD consists of movable mass M, a shock absorber in the form of elastic-damping constraints with parameters K, C, and a loading plate transferring the shock-absorber response to the structure. The principle of operation of the impactor is as follows: mass M falling freely from height h transfers the impact impulse and dead weight load $G = \mathrm{Mg}$ to the shock-absorber. The latter undergoes deformation and transmits force $Q(t)$ to the tested structure. In the course of the return motion the mass separates from the shock-absorber. The purpose of the shock-absorber is to soften the effect of the impact impulse and to convert it into a technical impulse with finite parameters. Thanks to this the structure is not at risk of sustaining surface damage. A pictorial diagram of FWD is shown in Fig. 1. The deflections of the pavement structure are measured by sensors (geophones) arranged along the axis of loading (directly under the loading plate) and in additional points, at fixed distances from the loading plate.

Dynamic load $Q(t)$ and the displacement $q_i(t)$ of the system boundary surface points, caused by the load are the basis for identifying the sought elasticity moduli of the system layers. The identified elasticity moduli are "substitute" modules globally characterizing the layered heterogeneous pavement. Therefore they should not be directly identified with the values of the moduli obtained from tests on system samples.

3. Transformation of impact test results into static test substitutes [5]

By carrying out the impact test one gets a set of oscillograms of displacements $q_i(t)$ and an oscillogram of resultant load $Q(t)$. It

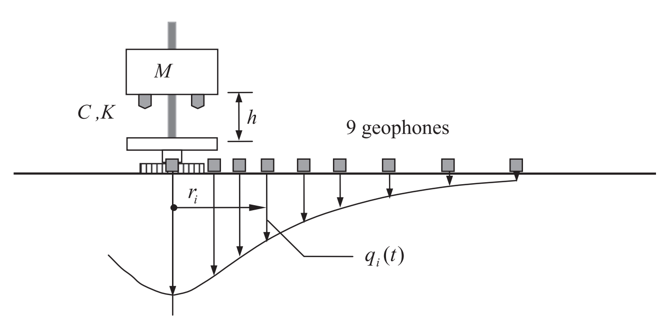

Fig. 1. Schematic of FWD.