Construction and Building Materials 176 (2018) 583–592

Contents lists available at ScienceDirect

Construction and Building Materials

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

Comparative study on using static and dynamic finite element models to develop FWD measurement on flexible pavement structures

Asmah Hamim [a], Nur Izzi Md. Yusoff [a,*], Halil Ceylan [b], Sri Atmaja P. Rosyidi [c], Ahmed El-Shafie [d]

[a] Dept. of Civil and Structural Engineering, Universiti Kebangsaan Malaysia, Malaysia
[b] Dept. of Civil, Construction and Environmental Engineering, Iowa State University, USA
[c] Dept of Civil Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia
[d] Dept of Civil Engineering, Universiti Malaya, Malaysia

HIGHLIGHTS

- A FE model was developed using static and dynamic analyses in ANSYS program.
- Transient dynamic analysis is best method for simulating FWD test by using FEM.
- A 5000 × 5000 mm model geometry is sufficient for developing an FE model.

ARTICLE INFO

Article history:
Received 15 February 2018
Received in revised form 7 May 2018
Accepted 8 May 2018

Keywords:
Finite element
Falling weight deflectometer
Flexible pavement

ABSTRACT

The deflection basin obtained through backcalculation analysis is compared with the measured deflection basin to determine the moduli of each pavement layer. Most computer programs use multi-layered elastic theory (MET) to perform backcalculation for determining deflection basin. Other structural analysis techniques, such as finite element method (FEM) and finite difference method (FDM), can be used to model flexible pavement structures when conducting FWD tests. Unlike FEM, MET analysis does not take into account nonlinear materials and dynamic loading. This study aims to develop a better finite element (FE) model by using the static and dynamic analyses in the ANSYS computer program. A comparative study was conducted by using varying sizes of model geometry and different types of elements and sizes to determine how they affect the developed FE model. The results of the analyses show that transient dynamic analysis is the best method for simulating FWD test. The percentage of errors between FE deflection basin and measured deflection basin range between 0.94 and 5.01%. Model geometry of 5000 × 5000 mm is sufficient to produce a good deflection basin which approximates the measured deflection. To ensure the accuracy of the developed model, the information on material properties must be valid. Additionally, finer and higher order elements should be used close to the loading region, for instance four or eight-node quadrilateral element (CAX4 or CAX8) with quadratic interpolation function.

1. Introduction

The structural condition of a pavement must be evaluated to determine its remaining life and identify the best method for rehabilitation. Non-destructive testing (NDT) is the most frequently used method for examining the conditions of pavement structures. NDT measures the stress–strain properties of pavement layers at relatively low strain levels. The two main categories of NDT are surface deflection basin and surface wave methods. The most frequently conducted NDT is the falling weight deflectometer (FWD) test, which is classified in the surface deflection basin category [1–3].

In the FWD test an impulse load is imposed on the pavement surface by dropping a mass of weight on a circular plate which has a rubber seal placed between it and the pavement surface to prevent a direct impact of the load. Sensors and geophones located at several radial offsets are used to measure the surface deflections directly under the plate. The measurement made by each geophone represents the deflection of a pavement structure at a particular location [1,2,4,5]. For instance, the measurement for the

* Corresponding author.
E-mail addresses: izzi@ukm.edu.my (Nur Izzi Md. Yusoff), hceylan@iastate.edu (H. Ceylan), atmaja_sri@umy.ac.id (S.A.P. Rosyidi), elshafie@um.edu.my (A. El-Shafie).

https://doi.org/10.1016/j.conbuildmat.2018.05.082
0950-0618/

deflection of the top layer is made by the first geophone or at the center of the loading plate.

FWD data is frequently used for performing back calculation analysis [6]. Backcalculation of the measured deflection basin of an FWD test can be used to derive the elastic modulus of each pavement layer [1,4,5,7]. The backcalculation of layer moduli involves two steps. The first step calculates deflections at various radial offsets from the center loading which represents the deflection basin, and the second step compares the calculated deflections with the measured deflections by using proper error minimisation algorithm to determine the layer moduli combination [8–10]. Among the structural analysis techniques used to obtain the calculated deflections in the first step of back-calculation analysis are multilayered elastic theory (MET), finite element method (FEM), and finite difference method (FDM) [1,4,11].

Most backcalculation analysis programs, such as BISDEF, ELSDEF, MODULUS, MODCOMP, WESDEF, and EVERCALC, use MET to calculate the deflections in FWD test [10,12,13]. A review of the literature shows that very few programs use FEM to address the conditions of an FWD test and the properties of a pavement layer during deflection analysis since most of backcalculation analysis programs were developed prior to the computer technology revolution of the 1980s. Since then most researchers have focused only on modelling FE for flexible or rigid pavement structures, with very little attention being given to analysis of FWD deflection basin [9].

Tarefder and Ahmed [9] used FEM to perform dynamic and static analysis of FWD deflection basin which takes into account nonlinear materials. They used ABAQUS to develop both axisymmetric and quarter cube models to simulate the time-deflection histories of an FWD test. They compared the results of dynamic, static, and field deflection basins and found that the deflection basins generated by the dynamic and static analyses are very similar to the measured deflection basin. The result of static analysis is closer to the measured deflection basin compared with that generated by the dynamic deflection basin. The axisymmetric model yields better results than the quarter cube model.

Uddin and Garza [14] developed a 3D-FE model of a flexible pavement and imposed a dynamic load on the model to observe the response of the pavement structure. The model was simulated using the load time history of an FWD test. The 3D-FE half models, with and without infinite elements, were evaluated using Green's function and the results revealed the limitation of using infinite elements for pavement models. The analysis also determined the time-dependent deflections at different frequencies. A natural frequency of 8 Hz was determined in the analysis. The researchers also noted that damping resulted in smaller peak deflection.

Kuo and Chou [15] used ABAQUS to develop the procedures for building a 3D FE model of flexible pavement by performing static analysis. A semi-infinite elastic solid was modeled and compared with the calculated displacement and stress by using the Boussinesq solutions to obtain guideline for model size and meshing. The model should consist of finite elements that are at least three times the loading diameter. Infinite elements should be used beyond the boundary of the finite elements. The viscoelastic behavior of the pavement structure was also validated under wheel loading. Results show that the model can properly simulate the behavior of a flexible pavement and can be used to predict pavement response.

Hadi and Bodhinayake [16] used the FE ABAQUS to model a three-dimensional pavement structure which was then subjected to static and cyclic loadings while taking into account the linear and nonlinear material properties of the pavement layers. Results show that, when the pavement structures are assumed to have static load and linear elastic materials, the deflections above the subgrade layer are higher than the anticipated values or the measured deflection. Results also show that the calculated displacement closely approximates the measured displacement under the assumptions of cyclic loading and nonlinear materials.

Shoukry et al. [17] used DYNA3D to develop a 3D FE pavement structure model, and imposed a dynamic load on the model to observe its dynamic response when conducting an FWD test. All layers are assumed to be elastic material. They also investigated the effects of the interface of bonded and unbonded layers on pavement response. The researchers concluded that the strength of the bonds between layers, especially those for flexible pavements, influenced the results of the FWD test. Unfortunately, their models are not valid since no comparison with field measurements was made.

In conclusion, the question frequently raised by the research community when using FEM for pavement structures is how to produce a simple model which reduce computation time while increasing the accuracy of pavement response. Engineering decisions with regard to the type of model, size of model geometry, type and size of elements used, load condition assigned, etc. must be made to develop better FE models with higher accuracy and shorter computation time.

It is important to use an appropriate analysis for the FE model. Three different approaches can be employed in pavement analysis, namely static, quasi-static, and dynamic transient analysis. The static approach has been traditionally used in multilayered elastic analysis. The quasi-static approach is based on the concept of moving a load to subsequent positions along the pavement for each step and assuming that the load is static at each position. This approach ignores inertia or damping effect. Dynamic transient analysis is dependent upon two important factors: the inertia associated with the moving load and the dependency of material properties on loading frequency [18]. This paper only looks at static and dynamic analyses in selecting the best analytical approach which should be used for flexible pavement analysis in FWD test by observing the accuracy of vertical deflection which occur in the deflection basin.

The objective of this study is to develop a better FE model for pavement structures by using different methods of analysis and different sizes of model geometry, as well as taking into account the viscoelastic properties of asphalt concrete under both static and dynamic loading. Evaluation was done by comparing the deflection basin generated by the FE models and the field measurements.

2. Methodology

The general purpose FE program, ANSYS, was used to develop all FE models in this study. The FE models were developed in two stages:

i. In the first stage the FE models were developed using both static and dynamic analysis methods to determine which of the two methods is more suitable for modelling a flexible pavement structure for FWD test.
ii. In the second stage a comparison was made by increasing the size of model geometry and changing the size and type of the element to determine whether these factors have any affect on the accuracy of the developed FE model.

The FWD data used in this study was provided by Edgenta Environmental & Material Testing Sdn. Bhd. For the pavement evaluation conducted on Jalan Negeri (P10) from Batu Maung to Jalan Sultan Azlan Shah, Pulau Pinang, Malaysia. Even though the pavement evaluation report [19] stated that the FWD test was conducted at 94 locations, the data for only three sites were utilized to evaluate the developed FE model. The FWD test was performed