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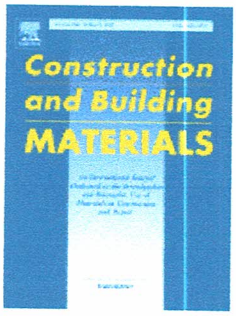

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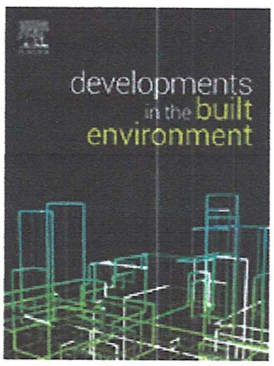

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Comparative study on using static and dynamic finite element models to develop FWD measurement on flexible pavement structures

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.

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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.
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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).

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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 using the Dynatest device. Information on layer thickness was obtained from core logs while data on layer properties was obtained through backcalculation analysis by using ELMOD.

2.1. Finite element analysis in ANSYS

The first step in using ANSYS is to select the appropriate method of analysis which will be used to evaluate the developed FE model. Although several methods can be used to do the evaluation, two methods, i.e. static structural analysis and transient dynamic analysis, were chosen to evaluate the developed FE models by comparing the RMSE values generated by the FE model with that of the field measurement.

The displacement, stress, strain and force in a structure or component that are caused by imposed loads can be determined using static structural analysis without taking into account the effects of inertia and damping. Steady-state loading and response are assumed to vary slowly with time. Thin models show better performance with a direct solver in ANSYS while bulky models show better performance with an iterative solver [20]. In the FE method, the overall equilibrium equation for linear structural static analysis can be written as

$$[K]\{q\} = \{f\} \tag{1}$$

where [K] is total stiffness matrix, {q} is total nodal displacement vector, and {f} is total load vector. ANSYS will automatically choose either a direct or iterative solver based on the type of analysis and model of geometry.

Transient dynamic analysis, which is also known as time-history analysis, is used to determine the dynamic response of structures under any general time-dependent loads by taking into account inertia and damping effects. This type of analysis can be used to determine time-varying displacement, strain, stress, and force under any combination of static, transient, and harmonic loads [20]. The basic equation solved by the transient structural analysis is:

$$[M]\{\ddot{u}\} + [C]\{\acute{u}\} + [K]\{u\} = \{P\} \tag{2}$$

where [M] is mass matrix, [C] is damping matrix, [K] is stiffness matrix, {P} is external force vector, $\{\ddot{u}\}$ is nodal acceleration vector, $\{\acute{u}\}$ is nodal velocity vector, and {u} is nodal displacement vector.

ANSYS uses the Newmark time-integration and the Hilber–Hughes–Taylor (HHT) method to solve Eq. (2) at discrete time points. The dynamic analysis of Eq. (2) takes into account mass inertia and damping effects. Inertial force is mass multiplied by acceleration, where acceleration is the second derivative of displacement. Dissipative contribution is determined by damping properties. Damping could be caused by an arbitrary damping factor, a friction factor, or the behavior of a viscoelastic material. Additional structural or mass damping is not required since the asphalt concrete layers have been assigned viscoelastic properties. On the other hand, the elastic aggregate base and subgrade layers do not have such energy dissipation sources, hence a general damping rule is required for these layers. A frequently used spectral damping scheme in structure dynamic analysis is Rayleigh damping with a maximum ratio of 5%.

2.2. Developing a finite element model

The general steps for developing an FE model for a multilayered flexible pavement structure for an FWD test are: 1) selecting model geometry, 2) assigning layer properties, 3) meshing the model, 4) defining boundary conditions, and 5) assigning load conditions. The following paragraphs will describe each of these steps. Analysis to determine the response of pavement structures, such as stress, strain, and deflection can be done after developing the model.

2.2.1. Model geometry

Pavement structures extend infinitely in vertical and horizontal directions in accordance with the semi-infinite half-space assumptions in layer elastic theory. Therefore, the geometry which will be used to develop the FE model must be determined to ensure the accuracy of pavement response under loading condition [21]. This entails determining the setup of the FWD test, the type of geometry analysis, and the size of model geometry. According to the pavement evaluation report, all FWD points are flexible pavements with four layers, namely surface, base, subbase, and subgrade layers.

Fig. 1 shows the pavement layers and region that are affected by the FWD test. Seven sensors, which are located 0, 300, 600, 900, 1200, 1500 and 2100 mm from the 300 mm diameter load plate, measured the vertical deflections. A short load pulse was applied on the 150-mm radius load plate to measure the vertical deflections at each sensor. Deflection is assumed to be equal in all radial direction. The deflection is maximum at the center of the load, or 0 mm from the sensor, and gradually decreases with increasing distance. Based on the setup shown Fig. 1, a decision can be made on whether to use a 2D plane strain, axisymmetric, or 3D cube to develop the FE model.

The geometry for analysis of pavement structures can be either two-dimensional (2D) plane strain, axisymmetric, or three-dimensional (3D) [9,21,22]. Several researchers have used 2D plane strain to develop a finite element model for pavement structures [21–23]. This requires only a short computation time and a small memory. The accuracy of this model is quite low since 2D plane strain models can only present load as a line load whereas the actual traffic load is an ellipse and is normally represented in a model by two semicircles and a rectangle [9,21].

Axisymmetric model is developed in a 2D geometry space; it has a cylindrical shape and rotates around a vertical axis [9,22]. It requires a slightly longer computation time than 2D plane strain models. The main advantage of this model is that it can solve a 3D structure problem in 2D by using cylindrical coordinates and

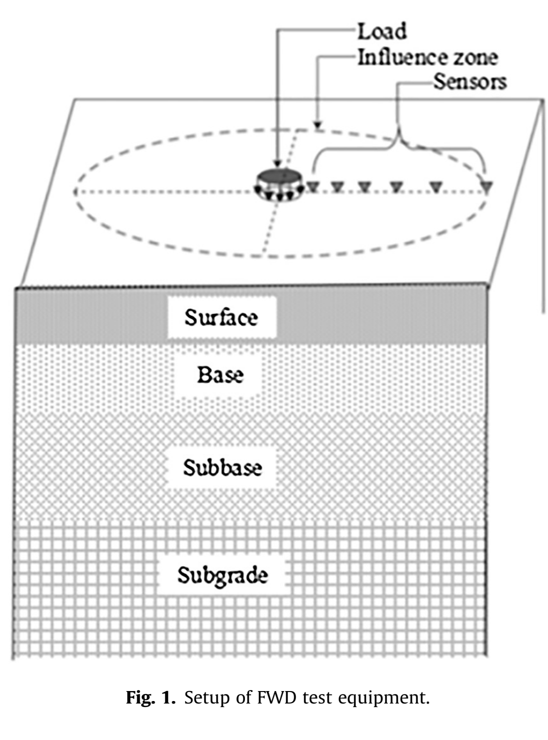


Fig. 1. Setup of FWD test equipment.

axisymmetric condition. However, this model can only be used for a single circular load and is not suitable for a dual tire configuration. Even though the model can be used for a special case of all-round radial shear, it is not able to take into account interface shear. This model does not have the ability to take into account any discontinuity in pavement structures, such as joint and cracks, or shoulder conditions. Therefore, this model is only suitable for pavement analysis if the loading region is located far from shoulders and cracks [9,21]. Tarefder and Ahmed [9] have shown that axisymmetric model yields better results than quarter cube model.

A 3D model can take into account conditions of a pavement structure, such as multiple wheel loading, nonlinear properties of base materials, pavement distress, and culverts in the subgrade. It can also analyze models for new pavements or existing pavements with joints, cracks, and discontinuities by taking into account static or dynamic load, which is not possible when utilizing traditional 2D models. This model, however, requires a large storage capacity and is time-consuming, especially when the analysis involves nonlinear material properties [9,15,21]. Hence, an axisymmetric model of multilayered flexible pavement structure was selected to develop an FE model which represents actual FWD testing condition in the field. Fig. 2 illustrates the axisymmetric model of pavement structure under FWD testing condition.

Although pavements are infinite structures in a real situation, the present study finite in both vertical and horizontal directions. The size of geometry model was determined based on literature review and a comparative study of different domain sizes. In order to develop the best FE model, Duncan et al. [23] recommended a model geometry with a length of 50 times and 12 times the radius of the circular loading area in the vertical and horizontal directions, respectively. For models with vertical height, the works of Dunlop et al. in 1970, Yamada in 1970, and Koswara in 1983, which were mentioned in Tarefder and Ahmed [9], were taken into consideration. They stated that the vertical height of homogenous soil model should be equal to between 4 and 10 times the width of loading area for the loading effect to be negligible. Hjelmstad et al. [24] reported that the effect of boundary truncation is not significant when vertical length is 150 times larger than the load radius. Therefore, it can be concluded that the recommended vertical length is between 4 and 10, 50 and 150 times the radius of loading area.

The maximum deflection of an FWD occurs close to the loading area. Huang [28]stated that the deflection value for the last sensor

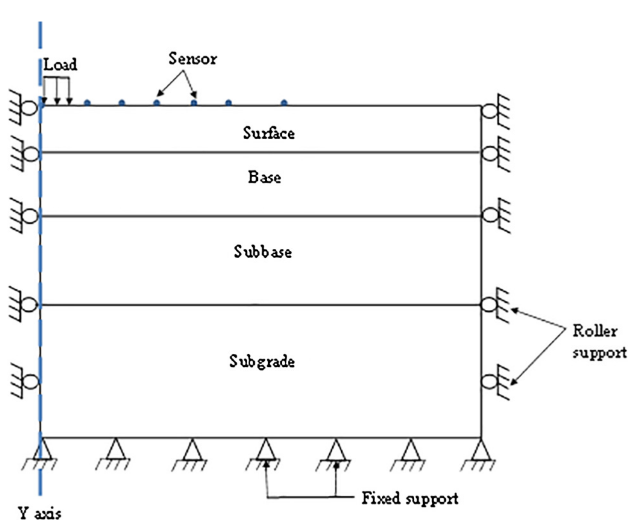


Fig. 2. Axisymmetric model of flexible pavement.

in an FWD test is typically very small and almost zero. Hence, the vertical stress in the subgrade layer or the stress deep in the subgrade layer could be negligible. Stress distribution has a profound impact on the size of model geometry. A small geometry size is sufficient to capture stress distribution since most deformation occurs in the subgrade area [25]. Hence, the horizontal length can actually be reduced. The horizontal length in the present study, however, is equal to the vertical length to simplify the FE models and to avoid boundary truncation.

Previous researchers used different geometry sizes to develop finite element models. For example, Tarefder and Ahmed [9] developed a 2D axisymmetric FE model with a vertical length that is 33.33 times the radius of the loading plate and a horizontal length that is 10 times the loading plate to model FWD deflection basins. Kim et al. [26] analyzed the effect of nonlinear behaviors of pavement foundation by constructing 2D axisymmetric and 3D models with vertical length and horizontal length that are 140 and 20 times the radius, respectively. In the present study, the FE model was developed based the size of model geometry used by Tarefder and Ahmed [9].

2.2.2. Layer properties

One of the important factors in finite element analysis is assigning material properties to each structure of a model. Since the material of each layer of a pavement structure have complex properties, absolute mathematical equation cannot be used to describe these layers. Thus, most pavement response models are developed based on layered theory and might not take into account the heterogeneity of asphalt concrete. In fact, most models are based on linear elastic and linear viscoelastic theories [27].

In this study, each model was developed as a multilayered elastic system comprising four layers of pavement structure: asphalt concrete as the surface layer, compacted granular material in the base and subbase layers, and a subgrade layer of natural soil. Each layer is modeled as a linear elastic, homogenous, isotropic material that is characterized by the Young modulus and Poisson ratio. The value of Young modulus for each model depends on the results of the backcalculation of FWD test. Poisson ratio has very minimal impact on the behavior of pavement structures [28]. Thus, the value of Poisson ratio in this study is assumed to be 0.35 for the surface layer, 0.4 for the base and subbase layers, and 0.45 for the subgrade layer. The thickness and material properties of the pavements at the three locations of the FWD test are presented in Table 1.

The asphalt concrete layer was modeled as a viscoelastic material. The Generalized Maxwell model shown in Fig. 3 is a mechanical model for characterizing viscoelastic materials. Blab and Harvey [29], Mulungye et al. [30], and Yan et al. [31] stated that the Generalized Maxwell model can be used to derive relaxation modulus in terms of Prony series and is by given by Eqs. (3) and (4).

$$G(t) = G_o + \sum_{k=1}^{k} G_i e^{-t/\tau_k} \tag{3}$$

$$K(t) = K_o + \sum_{k=1}^{k} K_i e^{-t/\tau_k} \tag{4}$$

where G_o and K_o are equilibrium modulus, G_i and K_i are relaxation modulus, and τ_k is relaxation time; all values are positive and constant. G_o and K_o is greater than 0 for viscoelastic solid, while for viscoelastic liquid both G_o and K_o are zero. The number of Maxwell elements, k, is 1, 2... and 8, and the relaxation time, $\tau_{k,} is 10^{(k-4)}$. G_i and K_i are determined by fitting Eqs. (3) and (4) using nonlinear least square regression [30].

Table 1
Layer thickness and properties of elastic material.

Point	Thickness (mm)			Modulus of Elasticity (MPa)			
	AC*	Base	Subbase	AC*	Base	Subbase	Subgrade
CH 200	240	70	160	769	84	103	205
CH 1450	220	363	265	840	130	231	124
CH 2300	170	182	495	1016	71	201	122

* AC = Asphalt concrete.

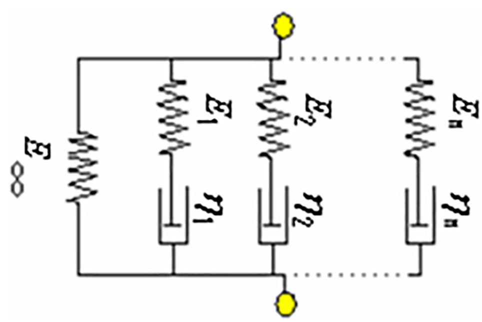


Fig. 3. Generalized Maxwell model.

In this study, the Simple Performance Testing (SPT) was used to predict the viscoelastic behaviors of asphalt concrete in terms of dynamic modulus and phase angle. The test was conducted at four temperatures (25, 35, 45 and 50 °C) and five frequencies (0.5, 1, 5, 10, 20 and 25 Hz) under continuous sinusoidal (haversine) load by monitoring the strain level. The results for dynamic modulus were converted to shear modulus, G, or bulk modulus, K, by using the Prony series analysis as required by ANSYS for viscoelastic material.

Fig. 4 shows the viscoelastic or rheological properties of the asphalt concrete layer for five locations along Jalan Negeri (P10). The solid line and marker points are the measured data from laboratory test and the predicted data from fitting results, respectively. The correlation coefficient (R^2) values of measured and predicted data for each location exceeds 0.99, which indicates that the data are a good match. The Generalized Maxwell model satisfactorily describes the viscoelastic properties of asphalt concrete for different loading frequencies at a certain strain level. Thus, these predicted data was used in the ANSYS finite element program to assign viscoelastic materials to the asphalt concrete layer.

2.2.3. Meshing of the model

The accuracy of finite element model depends on the type of meshing and element size. There are two types of elements, linear and quadratic. Linear elements employ a first order interpolation function while quadratic elements use a second order interpolation function. Although linear elements give a less accurate solution and its accuracy is very dependent on the value of the aspect ratio, it can generate a stiffness matrix fairly quickly. Contrarily, quadratic elements give a more accurate solution even when coarser mesh is used and the result is not significantly affected by the aspect ratio. It also takes a longer time to generate a stiffness matrix [21].

The size of elements is determined by the value of the aspect ratio. To ensure the accuracy of the developed model, the aspect ratio of the mesh elements must be kept between 1 and 2. Aspect

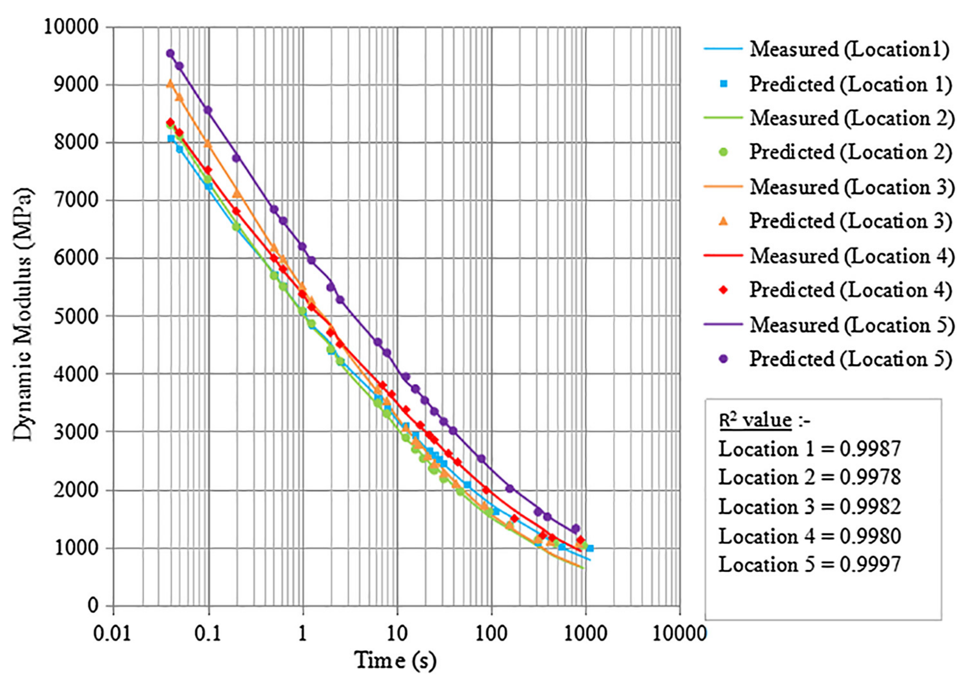


Fig. 4. Viscoelastic properties of AC at the Batu Maung site.

ratio is the ratio of the longest dimension to the shortest dimension of the elements [32]. Even though the quadrilateral elements are generated using second interpolation function, the value of the aspect ratio of the meshed model should be examined frequently. The distribution of aspect ratio values can be easily checked in ANSYS by selecting an aspect ratio on the mesh metric section.

In order to perform an optimum analysis, the elements of the region closest to the loading area must have the finest mesh in comparison with the furthest region. Even though fine mesh increases the number of elements, which consequently requires large computer memory and longer computing time, it will produce more accurate results [15]. Fig. 5 shows the mesh of an FE model. The surface, base, and subbase layers are meshed with the smallest elements and the subgrade layer is meshed with coarse elements.

2.2.4. Boundary condition

Assigning appropriate boundary condition to an FE pavement models could have an important effect on the predicted pavement response. Boundary condition can be divided into two categories, essential and natural boundary conditions. In practice, essential boundary condition is usually applied in structural analysis problems. One example of an essential boundary condition is support, which is used to restrain the movement of rigid bodies. Regardless of the loading condition, supports such as roller, fixed, hinge, etc. should be assigned to an FE model to prevent infinite displacement.

Several researchers have applied such boundary conditions in their works. For instance, Kim et al. [26] built an axisymmetric model by using roller vertical boundary node and fixed supports for the bottom boundary node. Helwany et al. [33] used DACSAR to develop an axisymmetric model by restraining the bottom subbase layer from any vertical movement, and was able to demonstrate the rigidity of the subgrade layer. Saad et al. [34] developed a 3D FE model assigned with roller supports at all four vertical boundaries and fixed support at the bottom of the model.

In the present study, roller supports are assigned to the vertical left and right of each model to restrain horizontal movement and only allow vertical movement (Fig. 2). The bottom subgrade layer is assigned fixed support and horizontal and vertical movements are not allowed. The connection between two adjacent layers is

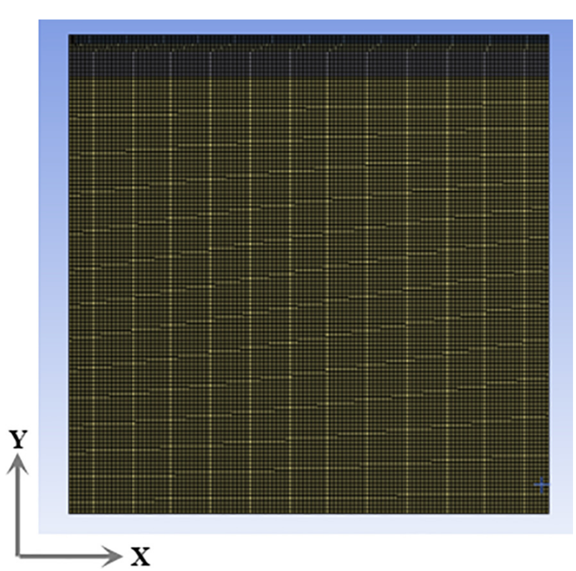


Fig. 5. Mesh of an FE model.

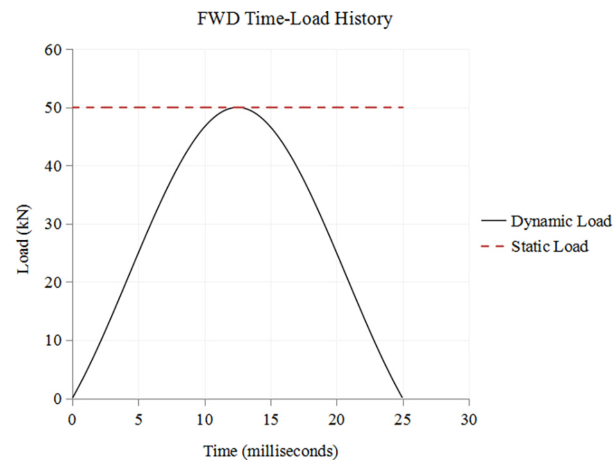


Fig. 6. Load pattern of an FWD test.

assumed to be fully bonded with no gap. Slip is not allowed between two connected layers.

2.2.5. Loading condition

In an attempt to improve the accuracy of the predicted pavement response, the FE model was used to simulate field loading condition. The FWD load has a half sine waveform and is also known as dynamic load. Based on the actual field test and pavement evaluation report for this site, an impulse load with a peak magnitude of 50kN was imposed on a 300 mm diameter loading plate for approximately 25 ms. A pressure of 700 kPa was assigned to the loading area of the developed FE model. Fig. 6 shows the time-load history of FWD where the dynamic peak load of 50kN is assumed to be attained at 12.5 ms. For a static load, a magnitude load of 50kN is assumed to be constant during the FWD test.

3. Results and discussion

This paper reviews two methods of analysis, namely static structural and transient dynamic analyses, and compares the two methods. The Workbench Help in ANSYS recommends that static analysis should be performed first to facilitate understanding of the effect of nonlinear and dynamic problem on structural response. Results of peak vertical deflections (predicted data) for all sensors were compared with the measured deflection basin of an FWD test (measured data) and the accuracy of the developed model was evaluated by computing the RMSE of both data.

3.1. First stage of model development

In first stage, the FE model was developed using 5000 mm × 5000 mm model geometry in the vertical and horizontal directions. The vertical and horizontal boundaries have a length that is 33.33 times the radius of a loading plate of an FWD test [9]. Each layer is assumed to be a linear elastic, isotropic homogenous material. Viscoelastic properties were also assigned to the asphalt concrete layer. The mesh model comprises 50 mm fine element and 80 mm coarse element. The FE models were meshed using a four-node quadrilateral element (CAX4) with a quadratic interpolation function. Static and dynamic loads were imposed on the FE model and boundary conditions were set as described earlier.

3.1.1. Deflection basin

Fig. 7 shows the difference in the deflection basins obtained through from field measurement and both FE analyses for the

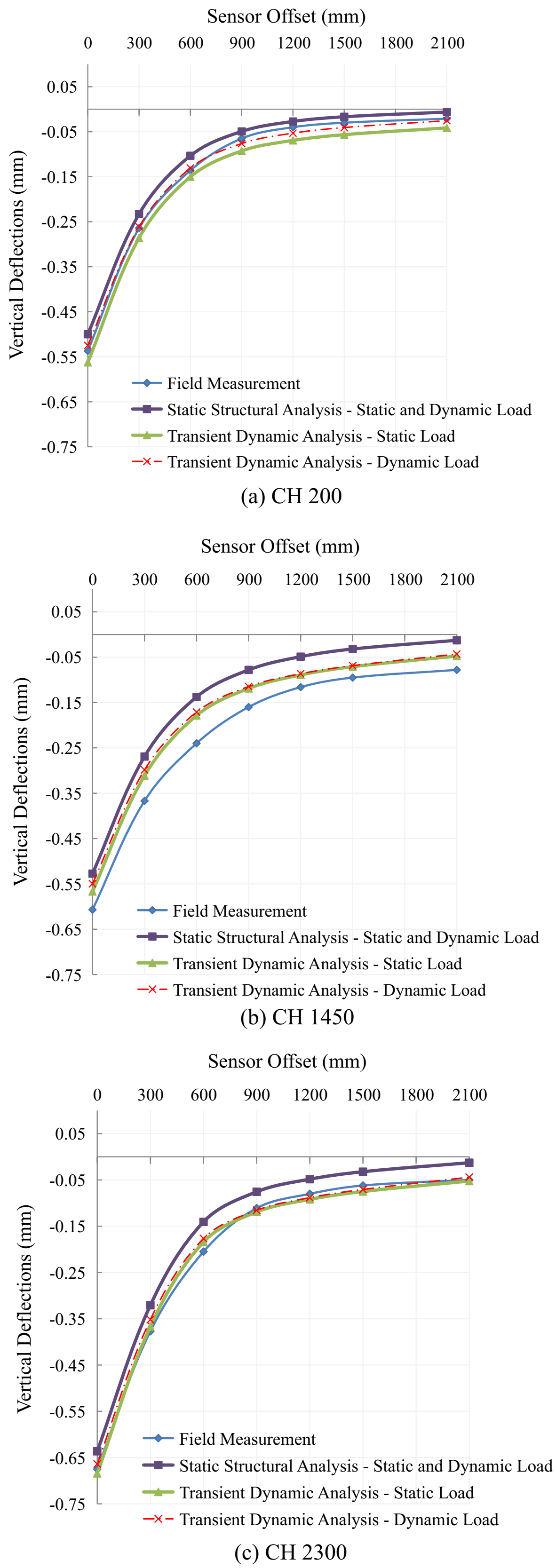


Fig. 7. Deflection basin for dynamic and static methods of analysis.

three locations of the FWD test. The deflection is maximum at 0 mm and diminished with increasing distance. The deflection value for each sensor obtained through the static structural analysis is similar for both static and dynamic loads. The deflection basins produced by the transient dynamic analysis are very similar for both static and dynamic loading conditions, and is a close approximation of the measured deflection basin. The percentage of RMSE was calculated to determine the approximation of deflection basins to the measured deflection basin.

Fig. 7(a) shows that the deflection basin for transient dynamic analysis under a dynamic load of CH 200 is a very close approximation of the measured deflection basin with an RMSE of only 0.94%. Other deflection basins in Fig. 7(a) show a very good correlation with the measured deflection basin with the percentages of RMSE of 2.41% for transient dynamic analysis under static loading, and 2.45% for static structural analysis under both static and dynamic loading.

Nevertheless, the deflection basin produced by the transient dynamic analysis under static loading gives the closest approximation to the measured deflection basin with an RMSE of 4.21% and 1.20% for CH 1450 and CH 2300, respectively, when compared with the measured deflection basin shown in Fig. 7(b) and (c). The same analysis for dynamic load produced deflection basins with RMSE of 5.01% and 1.58% for CH 1450 and CH 2300, respectively. It can be seen that the deflection basins produced by static structural analysis for both loading conditions have the least similarity with the measured deflection basin with RMSE of 8.10% and 4.36% for CH 1450 and CH 2300, respectively.

The results of the analyses show that transient dynamic analysis was able to produce a good FE model of flexible pavement structures with smaller RMSE in comparison to other static structural analysis methods. Even though static loading gives a more accurate result for vertical deflection, dynamic loading for transient dynamic analysis could also be utilized to determine deflection basin since the difference in RMSE between the two conditions is small.

3.1.2. Time-deflection history

Fig. 8 shows the time-deflection history for each FE analysis; the green and blue lines represent the time-deflection history for static structural analyses under static and dynamic load, respectively, while the red and purple lines represent time-deflection history for a transient dynamic analyses of static and dynamic load, respectively. Fig. 8(a)–(c) show the time-deflection histories for the three sensors that were positioned 0 mm, 300 mm and 600 mm from the center of the loading plate. The lines in the graphs of static structural analyses for static and dynamic loading show the same pattern as the assigned load, as can be seen in Fig. 6. The trends for CH 200, CH 1450, and CH 2300 are similar since static structural analysis only takes into account steady-state loading while ignoring inertia and damping effects. It should be noted that, for a static structural analysis under dynamic loading condition, maximum deflection occurred at 12.5 ms under all conditions.

On the contrary, the graphs of transient dynamic analyses for both static and dynamic loading conditions show a different trend from those of the static structural analysis of FWD. The result of transient dynamic analysis under static loading condition shows that vertical deflection increased with time until peak deflection occurs, after which it remained constant until the end of the FWD test. The graphs for transient dynamic analysis under dynamic loading condition are similar to those for static structural analysis for dynamic loading condition even though the maximum deflections of all sensors did not occur at 12.5 ms. For instance, maximum deflection occurred at 13.8 ms at the radial offset 0 mm for all three location of FWD test. Maximum deflections for the 300 mm and 600 mm radial offset occurred at 15.0 ms and

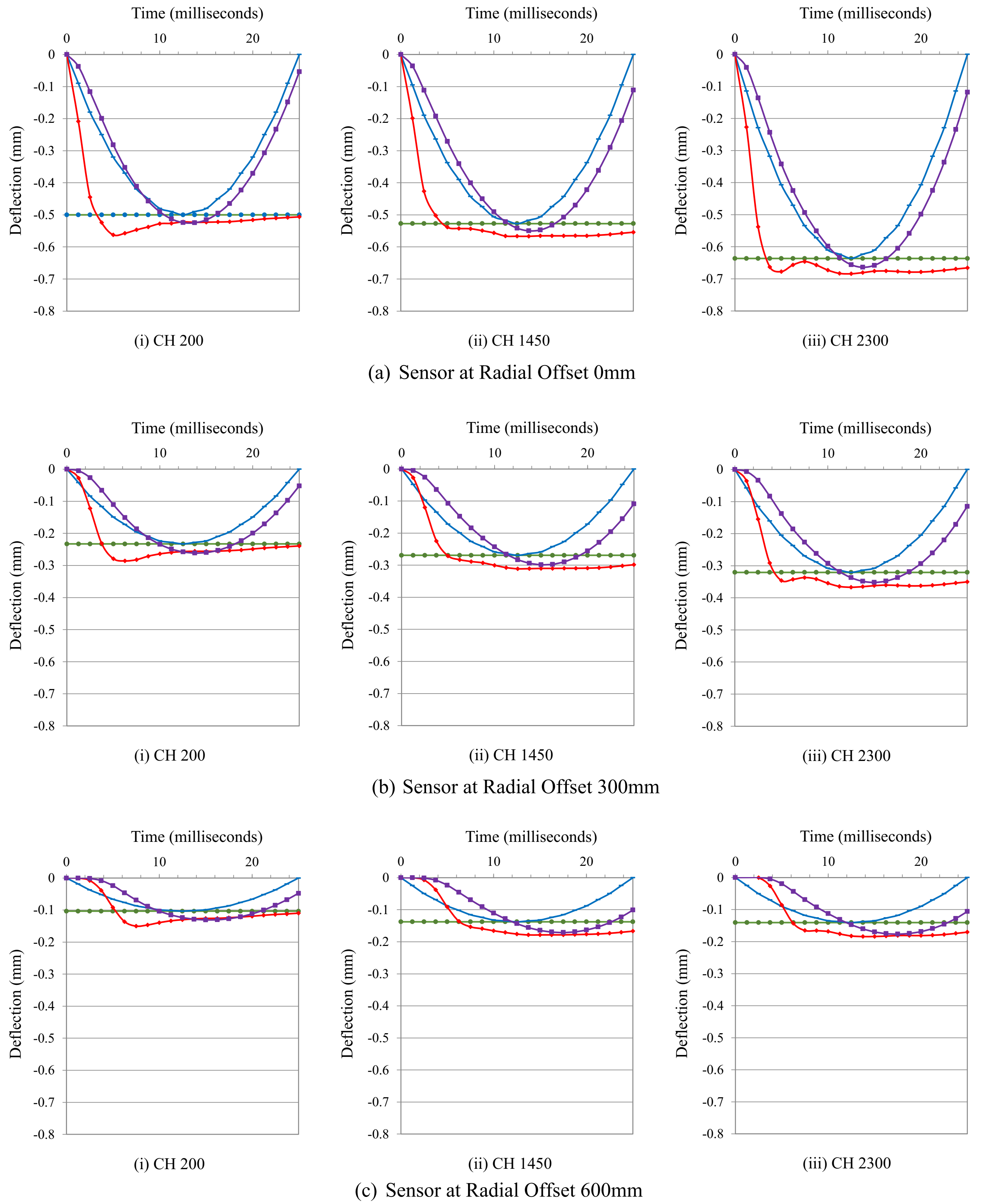
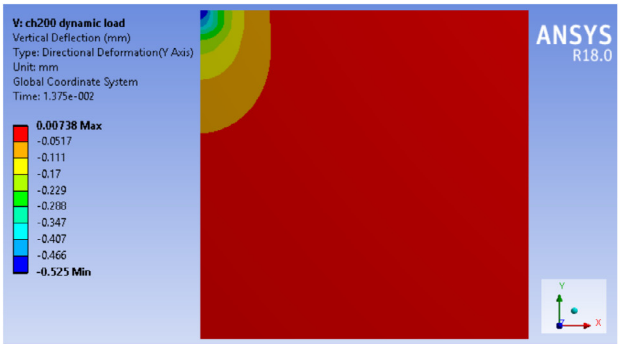


Fig. 8. Time-deflection history.

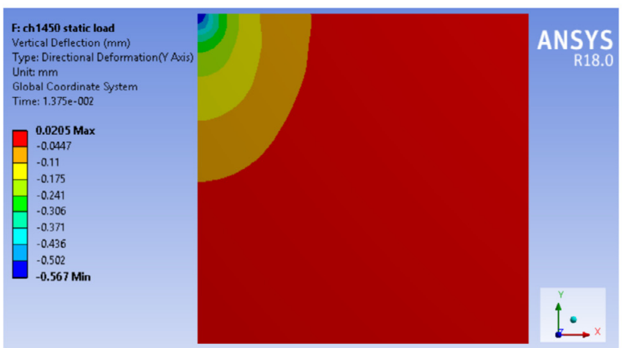
16.3 ms, respectively. This shows that there is a very small time lag in the occurrence of peak deflection. This is because transient dynamic analysis takes into account significant inertia and damping effects.

3.1.3. Contour plot of vertical deflection

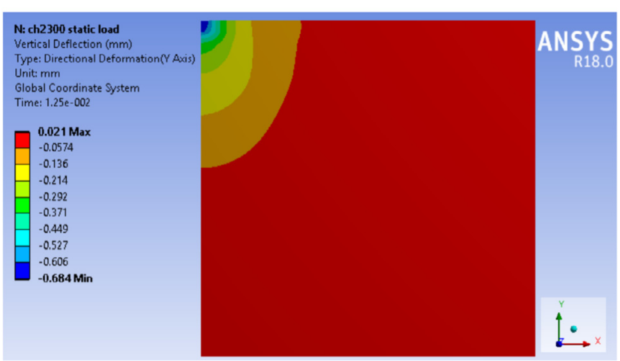
Fig. 9 shows the contour plots of vertical deflection for explicit dynamic analysis under dynamic load for CH 200 at 12.5 ms and static load for CH 1450 and CH 2300 at the end time. The contour



(a) CH 200



(b) CH 1450



(c) CH 2300

Fig. 9. Contour plot of vertical deflection.

was plotted to observe the distribution of vertical deflection throughout the model. The different colors represent deflection values. The color changes from blue to red and shows that vertical deflection decreases and approaches minimum in the red region. Maximum deflection occurred in the corner of the model where load was applied and deflection decreased with distance from the loading region. A further comparison was done by increasing the size of model geometry to determine whether the 5000 mm × 5000 mm model geometry is adequate without compromising the accuracy of the developed FE models.

3.2. Second stage of model development

In second stage, the FE models were developed by using the method which was determined to be better in first stage of analysis. The size of model geometry was increased to 10000 mm × 10000 mm to observe if it could improve the accuracy of the FE model. The material properties of each layer and the boundary conditions remain unchanged. The size of element was reduced, namely 40 mm for finer elements and 60 mm for coarse elements, by increasing the higher order element to an eight-node quadrilateral element (CAX8) with quadratic interpolation function.

Table 2 shows the time taken by the Central Processing Unit (CPU) to analyze the FE model, the number of nodes and elements, and the RMSE percentage when comparing the FE model with the field measurements. The table shows that the time required to analyze the data for 5000 × 5000 mm and 10,000 × 10000 mm model geometries are between 48 and 75 s and 71–108 s, respectively. Analysis of the axisymmetric FE model was completed fairly quickly since it involves a simple model; the short duration for the analysis is also due to the RAM of the computer. Table 2 also shows that CPU time increased very slightly when the size of the model geometry and the number of nodes and elements were increased.

The percentage of RMSE between the vertical deflections for the FE model and field measurement increased by 0.25% and 0.01%, respectively, as the size of geometry of CH 200 and CH 2300 was increased. Contrarily, the percentage of RMSE decreases by only 0.1% for CH 1450 when the size of model geometry was increased. Increasing the size of model geometry, assigning viscoelastic properties to asphalt concrete material, and using the higher order of elements and finest elements did not have any significant effect on the accuracy of the FE model.

4. Conclusion

The results of the comparison of both methods show that transient dynamic analysis is the better method for modelling flexible FE pavement structures for FWD testing under both static and dynamic loading conditions since RMSE ranges only between 0.94% and 5.01%. The percentage of RMSE for FE models and field measurements for a static structural analysis is slightly higher, namely between 2.45% and 8.10%. Hence, it can be concluded that 5000 × 5000 mm model geometry is sufficient for developing an FE model for flexible pavement structure used in an FWD test. The appropriate material properties for each layer, the type and size of elements, and boundary and loading conditions should be carefully determined when developing an FE model.

Table 2
Comparison of CPU Time, Number of Nodes and Elements, and Percentage of RMSE.

Point	5000 × 5000 mm			10,000 × 10000 mm		
	CPU Time (s)	Number of Nodes & Elements	Percentage of RMSE (%)	CPU Time (s)	Number of Nodes & Elements	Percentage of RMSE (%)
CH 200	70	9144 & 8946	0.94	121	129608 & 42921	1.19
CH 1450	75	9398 & 9198	4.21	108	133383 & 44176	4.11
CH 2300	56	7272 & 7100	1.20	99	81069 & 26800	1.21

Conflicts of interest statement

The Authors declare that there is no conflict of interest regarding the publication of this paper.

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