Apr. 2014, Volume 8, No. 4 (Serial No. 77), pp. 446-455
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

A Comparison of Different Approaches in Numerical Modeling of Pavement Granular Material

Behzad Ghadimi, Hamid Nikraz and Colin Leek
Department of Civil Engineering, Curtin University, Bentley 6845, Australia

Abstract: Modeling pavement granular materials have played a significant role in pavement design procedure. Modeling can be through an experimental or numerical approach to predict the granular behavior during cyclic loading. Current design process in western Australia is based on linear elastic analysis of layers. The analysis is largely performed through a well-known program CIRCLY which is applied to model bound pavement material behavior. The KENLAYER is one of the common pavement software models used for pavement design in the United State which performs non-linear analysis for granular materials. Alternatively, a general finite element program such as ABAQUS can be used to model the complicated behavior of multilayer granular materials. This study is to compare results of numerical modeling with these three programs on a sample constructed pavement model. Moreover, a parametric study on the effects of Poisson ratio over the surface deflection of the flexible pavement has been conducted. It is found that increase in Poisson ratio of asphalt layer will increase the surface deflection while the increase in Poisson ratio of granular layers decreases the surface deflection.

Key words: Flexible pavement, numerical analysis, ABAQUS, CIRCLY, KENLAYER.

1. Introduction

Design and construction procedures for transportation infrastructure such as road pavements, railway formations, and airfield pavements are aimed at assessing the permanent deformations and fatigue cracking of the bound or unbound layers. Currently, there is a growing trend to use computer software in design and analysis of pavement materials, however, each of these programs has its own specific ability and limitations. These computer programs are manipulated to model (called numerical modeling) behavior of flexible pavement under certain condition. Two different approaches are usual: first approach is using an analytical solution provided from theory of elasticity with calibration factors to match empirically observed behavior while second approach is implementation of finite element technique to solve general equilibrium of the whole layered system.

The advantages of numerical models for designers and researches are that they are considerably cheaper and they provide very rapid computation on standard computers. Moreover, in numerical modeling the full layered pavement system behavior can be observed and investigated.

1.1 Review of Elastic Computer Programs: CIRCLY 5.0 and KENLAYER

Based on linear elastic theory, an analytical solution of layered semi-infinite half-space can be calculated. The assumptions are that stress-strain behavior is linear elastic and the pavement domain has no limit in horizontal direction. In vertical direction, there is a horizontal stress-free surface at top of the medium while the bottom is extended to infinite depth.

Two well-accepted pavement design programs, KENLAYER and CIRCLY, calculate pavement system responses (stress, strain, deformation, etc.) based on elastic theory.

The KENLAYER Computer Program (Huang [1, 2]) is accepted computer program which can model pavement layers as linear elastic, nonlinear elastic or as

Corresponding author: Behzad Ghadimi, M.Sc., research fields: geotechnical engineering/pavement engineering. E-mail: behzad.ghadimi@postgrad.curtin.edu.au.

Mohr-Coulomb elastoplastic materials. The main core of KENLAYER is the solution for an elastic multilayer system under a circular loaded area.

The KENLAYER Computer Program can only be used to analyze flexible pavements with no joints. This program can use the superposition principle for multiple wheels. It can also use an iterative technique to solve non-linear problems [3].

Gedafa [3] used KENLAYER and HDM-4 to analyze flexible pavement performance. In this study, these two computer programs have been compared. It is concluded that KENLAYER is can be more easily applied to performance analysis while HDM-4 is a more powerful tool in the field of strategy analysis.

CIRCLY [4] is a computer program for pavement design and can be applied to material analysis. It can model materials either isotropic or anisotropic. The load is considered as the tyre pressure uniformly distributed over a circular area. The analysis is assumed to be under static condition and superposition principle is valid.

CIRCLY was developed as a geomechanical program in the Division of Applied Geomechanics of CSIRO (Commonwealth Scientific and Industrial Research Organization) of Australia. Then in 1987, the NAASRA (National Association of Australian State Road Authorities) used CRICLY in the Guide to Structural Design of Pavements. This is the basis for "Guide to Structural Design of Pavements" developed and modified by AUSTROADS (formerly NAASRA) in 1992 and 2004. The CIRCLY 5.0 (current version of the program) is written in FORTRAN IV [5].

One of the referred studies in which an interesting comparison has been presented was undertaken by Ullidtz [6]. In this paper, six pavement program including CIRCLY and KENLAYER were compared against the measured field data. Field data is collected from three full scale pavement projects from CEDEX (Centro De Estudios Y Experimentacion De Obras Publicas) in Spain, DTU (Technical University of Denmark) in Denmark and LAVOC (Laboratoire Des Voies De Circulation) in Switzerland.

A review of the mechanistic design approach in pavement design has been undertaken by Wardle et al. [7]. According to Wardle, "unbound layers should be 'sub-layered' in order to better model their non-linear response. If a non-layered model is used, the computed strains caused by a vehicle will be different, and the failure criterion that is then derived from performance data using the different strains will also be different." In this study, CIRCLY is manipulated to calculate the vertical strain for 4 t and 20 t wheel load and the results is plotted in different depth.

Hadi and Symons [8] have compared results of the CIRCLY program with a finite element model constructed in MSC/NASTRAN and STRAND. According to their study, CIRCLY resulted in a lower number of allowable repetitions based on AUSTROADS recommended loading.

Tutumluer et al. [9] compared the results of pavement modeling through finite element program GT-PAVE and CIRCLY for a cross anisotropic model. In this study, the two programs were used to calculate the elastic response of layered pavement system. Although both of these programs are based on an analytical solution, they are unable to produce "the exact" results. The reason is that in both programs, the calculation approach is numerical and there is a level of approximation in each.

1.2 Review of ABAQUS Application in Flexible Pavement Modeling

Advancing technology in computers is making it more attractive for engineers to use advanced computational methods instead of analytical solutions limited by computer power. One of the most accepted methods among the available options is the FEM (finite element method). The main advantage of FEM-based programs is their ability to model various types of mechanical loadings and behaviors in a two or three dimensional medium.

Recently the ABAQUS program, a general purpose

FEM program, has been employed to model layered flexible pavement system.

Zaghloul and White [10] have used ABAQUS to model the three dimensional behavior of a pavement layered system under dynamic loading.

Mallela and George [11], Uddin et al. [12] and Cho et al. [13] also employed ABAQUS in a three dimensional model. Kim et al. [14-16] have used the general purpose finite element computer program ABAQUS in their study on modeling the nonlinear behavior of the stress-dependent pavement foundation (subgrade).

Vuong [17] has investigated the effect of repeated loading on pavement granular materials. In this study, a nonlinear finite element has been used to predict the stress-strain response of the pavement system. Many loading conditions, including single, tandem, tri and quad axle have been chosen to validate the finite element analysis results.

Bodhinayake [5] has used the ABAQUS to model nonlinearity in subgrade soil while other pavement layers has been modeled as a linear elastic material.

In the current study, the ABAQUS software package is used to determine its capacity and compare the output with the KENLAYER and CIRCLY programs.

1.3 Current Study

The main purpose of this research is to compare three different programs which use different approaches to predict the behavior of pavement materials. To do so, three well-known programs which are: KENLAYER, CIRCLY and ABAQUS are manipulated to construct a sample layered pavement system. A fixed geometry and load condition is chosen for analysis. The analysis has been repeated whilst varying Poisson ratio individually to the asphalt layer, granular layer and subgrade to determine the sensitivity to this parameter, the results of analysis from each program have been extracted and compared.

2. Numerical Modeling

While there is a traditional inclination towards laboratory and field tests in pavement engineering, recently the numerical modeling option has attracted many researchers. Duncan et al. [18] first used the finite element approach in flexible pavements analysis. Huang [19] calculated stresses and displacements in nonlinear soil through finite element modeling. Since then many authors have used numerical modeling to calculate induced damage in pavement layers, including the asphalt layer, base and subgrade.

In the first step of this study, a sample layered pavement system has been modeled in CIRCLY, KENLAYER and ABAQUS. The result of surface deflection is then plotted and compared. In the next step, different Poisson ratios for each layer have been modeled and the results of the three programs are presented.

2.1 Characteristics of the Model

A sample section of a layered pavement with same thickness, geometry and loading characteristics is modeled in the aforementioned programs. Fig. 1 illustrates the geometry of the modeled pavement.

The material properties of the first trial run are listed in Table 1. All layers are assumed to behave linear elastically under a 0.75 MPa pressure loading, which is applied over a circular area of 92 mm radius. This is taken as a circular representation of the tyre pressure in the AUSTROADS method employed in CIRCLY (AUSTROADS [20]).

Materials properties for the first analysis are presented in Table 1.

2.2 Constructed Model in KENLAYER and CIRCLY

KENLAYER and CIRCLY are based on elastic theory. In three-dimensional elastic analysis, the stresses and strains are related to each other. Eq. (1) shows this relation [21]:

$$\begin{aligned} \varepsilon_{xx} &= \frac{1}{E}\left[\sigma_{xx} - \nu\left(\sigma_{yy} + \sigma_{zz}\right)\right] \\ \varepsilon_{yy} &= \frac{1}{E}\left[\sigma_{yy} - \nu\left(\sigma_{xx} + \sigma_{zz}\right)\right] \\ \varepsilon_{zz} &= \frac{1}{E}\left[\sigma_{zz} - \nu\left(\sigma_{xx} + \sigma_{yy}\right)\right] \end{aligned} \quad (1)$$

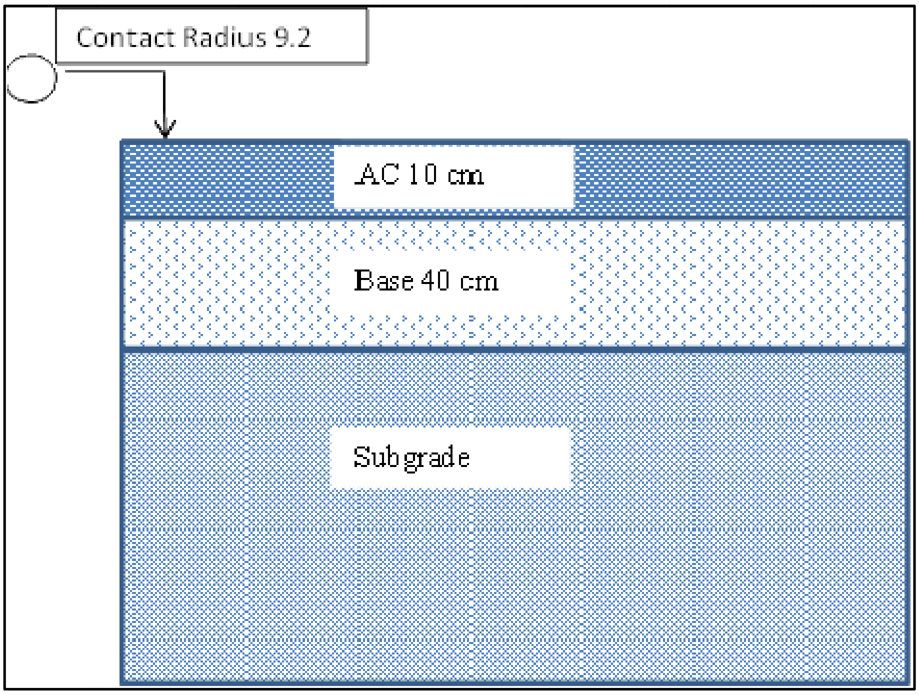

Fig. 1 Constructed model in KENLAYER and CIRCLY.

Table 1 Material properties for KENLAYER and CIRCLY programs.

Layer	Thickness (mm)	Elastic modulus (MPa)	Poisson ratio
Asphalt (AC)	100	2,800	0.4
Granular (Base/Subbase)	400	500	0.35
Subgrade	Infinite	62	0.4

where,

σ is the normal stress along the axes;

ε is the normal strain along the axes;

E is the elastic modulus of the materials;

v is the Poisson ratio.

However, in this study the models are constructed and analyzed in two dimensional axisymmetric conditions. When axisymmetric conditions are applied, the full three-dimensional equation can be reduced to Eq. (2):

$$\varepsilon_r = \frac{1}{E}(\sigma_r - \nu\sigma_z)$$
$$\varepsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_r) \qquad (2)$$

where,

σ_r is the radial stress;

σ_z is the vertical stress;

ε_r is the radial strain;

ε_z is the vertical strain;

E is the elastic modulus of the materials;

v is the Poisson ratio.

Based on Eqs. (1) and (2), one of the two influencing material properties in elastic modeling is Poisson's ratio. Whilst the overall design is relatively insensitive to variations in Poisson's ratio, an investigation over its effect on the surface deflection is of value.

To investigate the effects of material properties on the analysis, the geometry in Fig. 1 is assumed to be consistent in different section of the analyses (while materials properties are to modified).

For layered pavement systems, multi-layer elastic theory is applied where the pavement system is considered as horizontally infinite layers. These layers are of determined thickness in the vertical direction. In pavement analysis, it is also usual to consider the last layer (subgrade) as a vertically infinite layer. Therefore, the whole system is modeled as multi-layered semi-infinite half space. The other assumption applied in the elastic model used in CIRCLY and KENLAYER is a full friction condition between two consecutive layers. Finally, the surface of pavement system is considered as a frictionless layer causing no shear stress [5].

2.3 Finite Element Model

While CIRCLY and KENLAYER use an analytical equation for multi-layered half space medium to simulate the actual condition of pavement structure, the finite element approach tries to predict the mechanical response of the system through solving by equilibrium of forces. The assumption here is that the model should satisfy continuity of medium (no crack is modeled).

Although this method of modeling is more difficult, it has the advantage to model various types of loading conditions, geometry and material behavior. This capacity is implemented in ABAQUS program very effectively.

Fig. 2 illustrates the geometry of FEM model. The material properties are the same as listed in Table 1. However, the geometry of the model in ABAQUS cannot be the same as CIRCLY and KENLAYER because the horizontal and vertical dimension must be finite. To overcome this problem Duncan et al. [18] suggested a dimension of 50-times *R* (loading radius) in vertical and 12-times *R* in horizontal direction. Kim et al. [16] found a good agreement between results of the FE analysis and KENLAYER when the model dimension is 140-times *R* in vertical and 20-times *R* in horizontal direction. In this study, after several trial runs, the final dimension of model has been selected as 55.35 times *R* in horizontal direction and 108.70 times *R* in vertical direction.

Fig. 3 shows the constructed FE meshes for the axisymmetric 2D analysis. Vertical lines on both sides of the finite element model are bounded with roller boundary condition which permits the displacement in the vertical direction but prohibits it in the horizontal direction. The base of the model is fixed in every direction. The model contains 3,402 biquadratic axisymmetric quadrilateral reduced integration elements and 10,453 nodes.

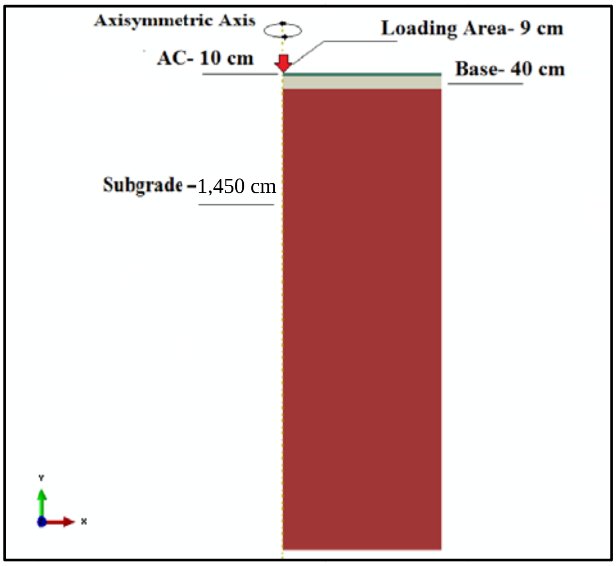

Fig. 2 Constructed model in ABAQUS.

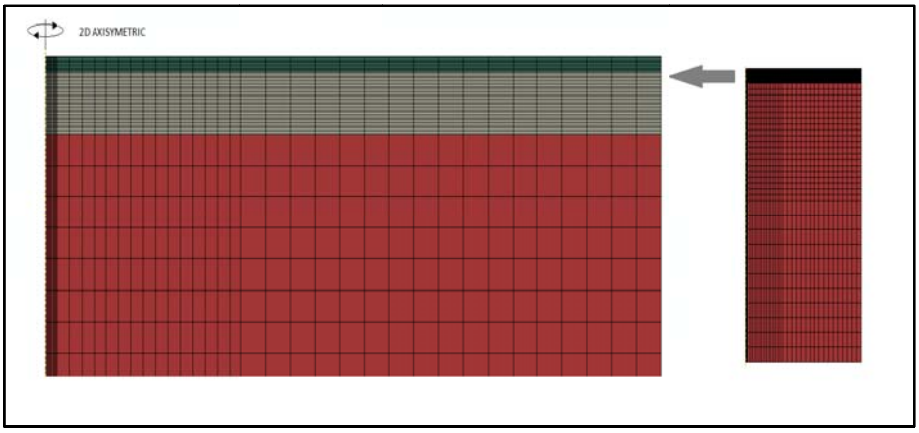

Fig. 3 Mesh properties of FEM.

The first step of the analysis is performed to verify the finite element model accuracy against the elastic solution models. The results of surface deflections calculated by each model are presented in Fig. 4. Whilst an acceptable agreement is observed, the surface deflection determined by ABAQUS is less than what is determined by KENLAYER and CIRCLY. It can be interpreted that the finite element mesh is behaving slightly "stiffer" than the analytical solution.

3. Effect of Poisson Ratio on the Numerical Results

The next step of this study was to determine the effect of variation in Poisson's ratio on the numerical prediction of surface deflection for the constructed model. This was achieved by applying six different Poisson ratios for each layer and determining the vertical displacement beneath the center of the tyre contact area. In each case where the Poisson's ratio of a selected layer is modified, the material properties for all other layers are maintained constant as presented in Table 1. For example, when the Poisson's ratio for asphalt layer is varying from 0.2 to 0.45, the Poisson ratio for the base and subgrade are assumed to be 0.35 and 0.4, respectively.

It is worth mentioning that the range of assumed Poisson ratios is beyond the accepted ranges, such as 0.2 for asphalt layer or 0.45 for granular base layer, but have been applied solely to investigate the trend in the behavior of the model and determine the sensitivity of the models to this parameter.

Figs. 5-7 illustrate the results of surface deflection for the variations in Poisson's ratios in each layer. For comparison purposes the results obtained from the three programs are presented conjointly.

Fig. 5 shows the effect of variations of Poisons ratio on the asphalt layer, and whilst the numerical magnitude of the calculation is different, the trend is the same for each model.

Fig. 6 shows the effect of variations of Poisons ratio on the base layer, and whilst the numerical magnitude of the calculation is different, the trend is the same for each model.

It can be seen that CIRCLY shows the largest values for the deflection in all cases, while the ABAQUS values are the lowest, and KENLAYER gives a result between these two.

However, the variation in the Poisson ratio for the base layer and asphalt layers leads to opposite trends in surface deflection. The increase of the Poisson ratio for

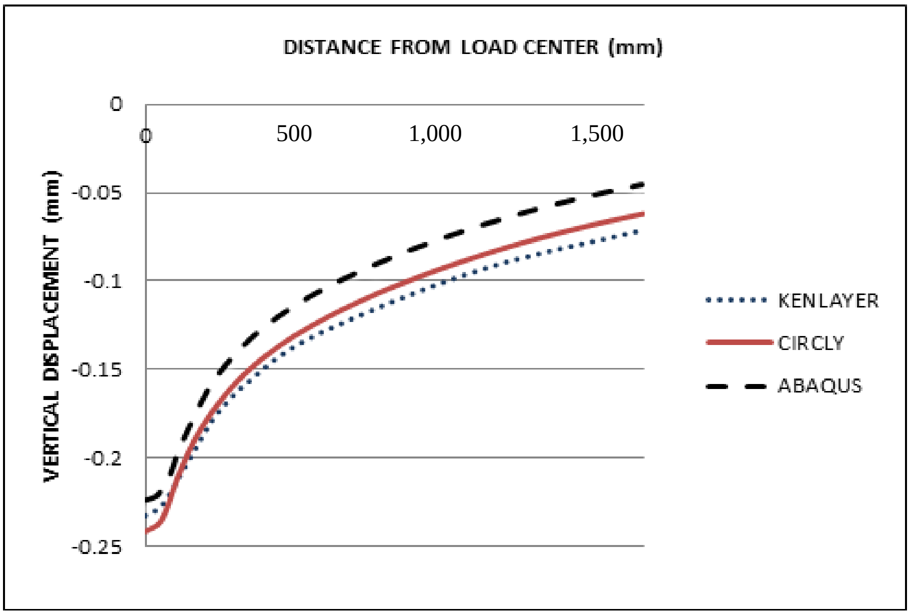

Fig. 4 Comparison of surface deflection.

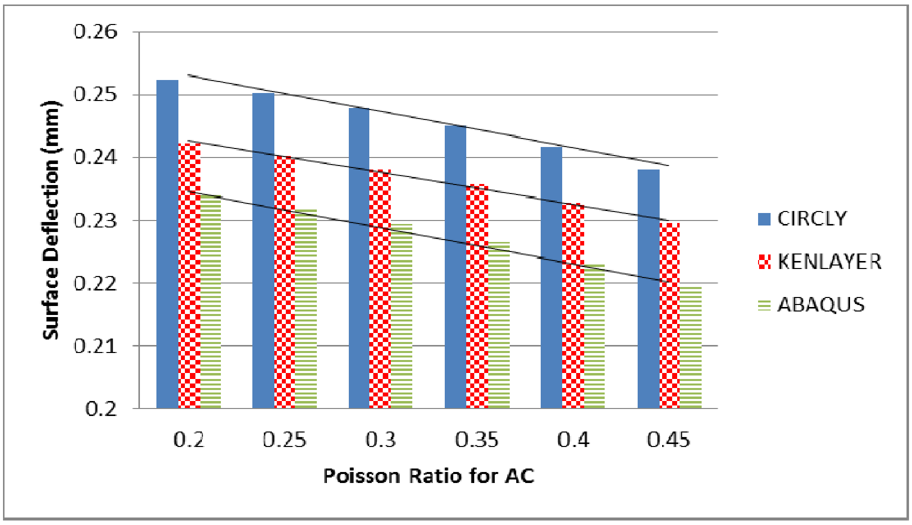

Fig. 5 Surface deflection vs. variation of Poisson ratio of the asphalt layer.

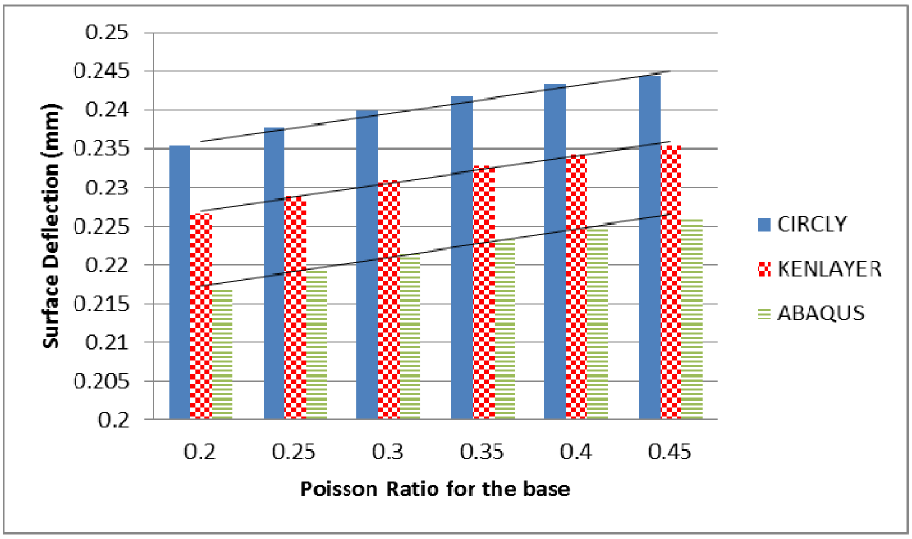

Fig. 6 Surface deflection vs. variation of Poisson ratio of the base layer.

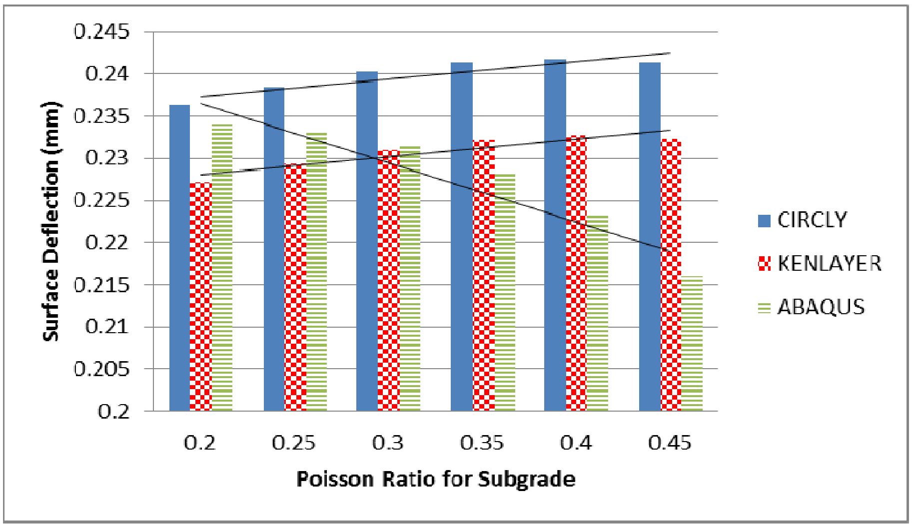

Fig. 7 Surface deflection vs. variation of Poisson ratio of the subgrade layer.

the granular base layer results in the increase of the surface deflection, where an increase in Poisson's ratio in the asphalt layer leads to a decrease in calculated deflection.

When Poisson's ratio for the subgrade layer is altered, unlike the case for asphalt and the base course layer, the three programs do not produce a common trend for deflection. As shown in Fig. 7, the calculated deflections from ABAQUS indicates decreasing deflection as Poisson's ratio is increased, where both CIRCLY and KENLAYER indicate the opposite trend. This is due to the effect of the boundary condition in FEM versus the analytical elastic solution. The finite element model requires finite boundaries in both vertical and horizontal directions and the assumption is made that a sufficiently large mesh size in the horizontal and vertical direction will behave as an infinite layer. However, the values predicted surface deflections from the FE model are in an acceptable agreement with the other two programs.

The maximum difference occurred when the subgrade Poisson's ratio was assigned a value of 0.45. CIRCLY determined the highest deflection at 0.241 mm and ABAQUS the lowest at 0.216 mm, an 11% difference. At a Poisson's ratio of 0.2, ABAQUS determined a deflection of 0.233 compared to a CIRCLY determination of 0.236. And at a Poisson's ratio of 0.3, KENLAYER and ABAQUS were in agreement.

The sensitivity of predicted surface deflections for the modeled pavement towards variation in Poisson's ratio in each layer is shown in Figs. 8-10. It is noted again that the Poisson's ratio of only one layer is varied in each trial run, with the other layers remaining constant.

The most sensitive layer to variations in Poisson's ratio in CIRCLY and KENLAYER is the asphalt layer. Fig. 8 shows the variation of surface deflection in CIRCLY where increasing Poisson ratio from 0.2 to 0.45 in the asphalt layer leads to decrease of surface deflection from 0.252 mm to 0.238 mm or 5.6%. In the case of Fig. 9 shows for KENLAYER the variation is from 0.242 mm to 0.229 mm or 5.3% for the same range.

Fig.10 shows the case for ABAQUS where the most sensitive layer is subgrade. Increasing the Poisson ratio of the subgrade from 0.2 to 0.45 resulted in decrease of surface deflection from 0.234 mm to 0.216 mm or 7.7%.

4. Conclusions

A sample of layered flexible pavement is modeled in

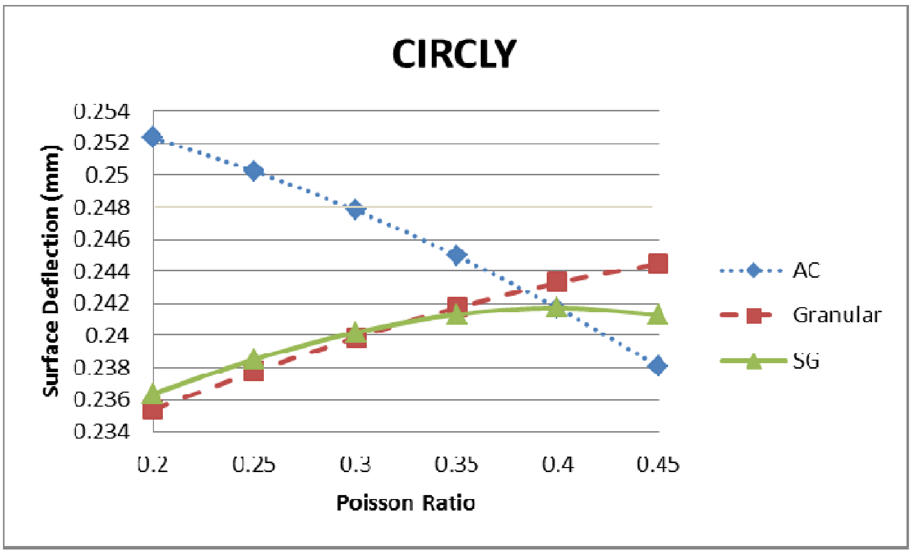

Fig. 8 Effect of the variation of Poisson ratio on the surface deflection calculated by CIRCLY.

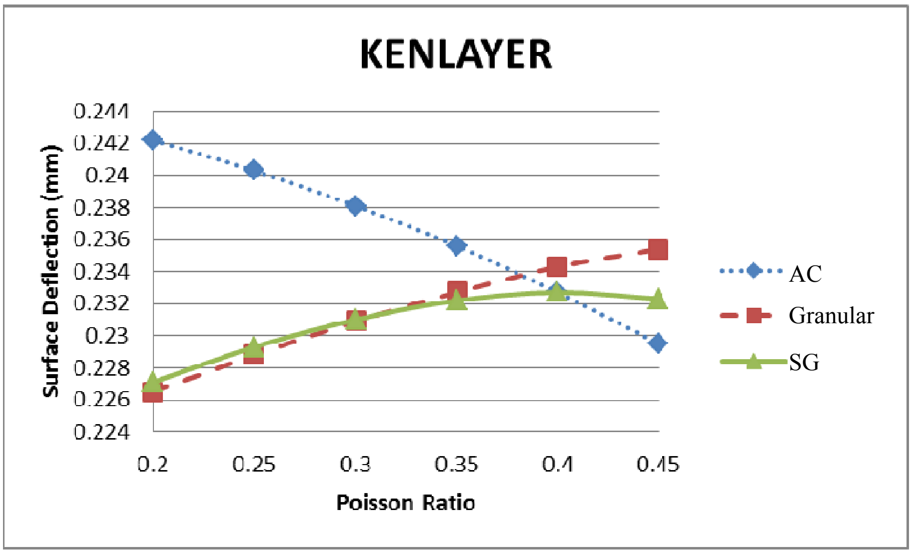

Fig. 9 Effect of the variation of Poisson ratio on the surface deflection calculated by KENLAYER.

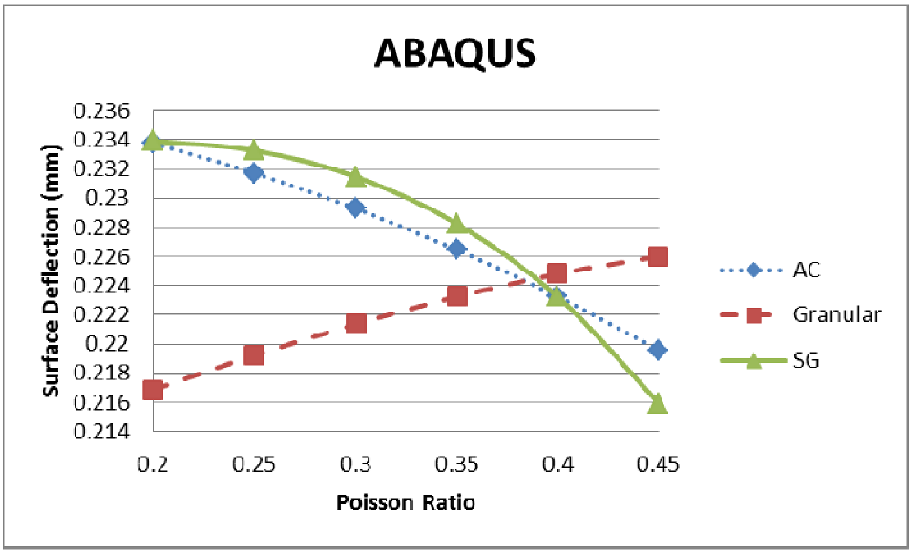

Fig. 10 Effect of the variation of Poisson ratio on the surface deflection calculated by ABAQUS.

three different programs that are CIRCLY, KENLAYER and ABAQUS. CIRCLY and KENLAYER are based on multilayer elastic theory while ABAQUS is a general purpose finite element programs. The Poisson ratio of the each layer was varied whilst the other two layers held constant, and the vertical displacement at the surface is compared in the three programs using the same loading conditions and material properties. While the general value of surface deflection are in acceptable agreement in all three programs there are dissimilarities in the predicted results and trends of responses. These differences can be attributed to the inbuilt assumptions and capabilities of each program.

The most fundamental difference is that both multilayer elastic programs model pavements of infinite horizontal dimensions, with an infinite depth subgrade, where the finite element model requires finite dimensions at all times.

The method of calculation which is used by KENLAYER and CIRCLY is different, they use different numerical integration technique that this can be the cause of different results.

References

[1] Y.H. Huang, Pavement Analysis and Design, Prentice-Hall Inc., New Jersey, USA, 1993.

[2] Y.H. Huang, Pavement Analysis and Design, Pearson Prentice Hall, Pearson Education Inc., USA, 2004.

[3] D.S. Gedafa, Comparison of Flexible Pavement Performance Using Kenlayer and HDM-4, Midwest Transportation Consortium, Ames, Iowa, 2006.

[4] L. Wardle, Program CIRCLY: A Computer Program for the Analysis of Multiple Complex Circular Loads on Layered Anisotropic Media, User's Manual: Division of Applied Geomechanics, Commonwealth Scientific and Industrial Research Organization, Australia, 1977.

[5] B.C. Bodhinayake, A study on nonlinear behaviour of subgrades under cyclic loading for the development of a design chart for flexible pavements, Thesis Collection, University of Wollongong, 2008, p. 868.

[6] P. Ullidtz, Analytical tools for design of flexible pavements in Keynote address, in: Proceedings of the 9th International Conference on Asphalt Pavements, Copenhagen, 2002.

[7] L. Wardle, G. Youdale, B. Rodway, Current issues for mechanistic pavement design, in: 21st ARRB and 11th REAAA Conference, ARRB Transport Research, Cairns, Australia, 2003.

[8] M. Hadi, M. Symons, Computing stresses in road pavements using CIRCLY, MSC/NASTRAN and STRAND6, Australian Civil Engineering Transactions 38 (2-4) (1996) 89-93.

[9] E. Tutumluer, D.N. Little, S.H. Kim, Validated model for predicting field performance of aggregate base courses, Transportation Research Record: Journal of the Transportation Research Board 1837 (2003) 41-49.

[10] S. Zaghloul, T. White, Use of a three-dimensional, dynamic finite element program for analysis of flexible pavement, Transportation Research Record 1388 (1993) 60-69.

[11] J. Mallela, K. George, Three-dimensional dynamic response model for rigid pavements, Transportation Research Record 1448 (1994) 92-99.

[12] W. Uddin, D. Zhang, F. Fernandez, Finite element simulation of pavement discontinuities and dynamic load response, Transportation Research Record 1448 (1994) 100-106.

[13] Y.H. Cho, B.F. McCullough, J. Weissmann, Considerations on finite-element method application in pavement structural analysis, Transportation Research Record: Journal of the Transportation Research Board 1539 (1996) 96-101.

[14] M. Kim, E. Tutumluer, Modeling nonlinear, stress-dependent pavement foundation behavior using a general—Purpose finite element program, in: Pavement Mechanics and Performance—Geo Shanghai International Conference, Shanghai, 2006.

[15] M. Kim, Three-dimensional finite element analysis of flexible pavements considering nonlinear pavement foundation behavior, Ph.D. Thesis, University of Illinois, Illinois, 2007.

[16] M. Kim, E. Tutumluer, J. Kwon, Nonlinear pavement foundation modeling for three-dimensional finite-element analysis of flexible pavements, International Journal of Geomechanics 9 (2009) 195-208.

[17] B.T. Vuong, Validation of a three-dimensional nonlinear finite element model for predicting response and performance of granular pavements with thin bituminous surfaces under heavy vehicles, Road & Transport Research: A Journal of Australian and New Zealand Research and Practice 17 (1) (2008) 3-31.

[18] J.M. Duncan, C.L. Monismith, E.L. Wilson, Finite element analyses of pavements, Highway Research Record Highway Research Board 228 (1968) 18-33.

[19] Y. Huang, Finite element analysis of nonlinear soil media, in: Proceedings of Symposium on Application of Finite Element Methods in Civil Engineering, Vanderbilt University, Nashville, The Netherlands, 1969.

[20] AUSTROADS, Pavement Design—A Guide to the Structural Design of Road Pavements, Austroads, Sydney, Australia, 2004.

[21] H.S.Yu, Plasticity and Geotechnics, Springer, US, 2006, p. 544.