Assessment of Computer Programs for Analysis of Flexible Pavement Structure

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Five computer programs were reviewed and evaluated to establish the most appropriate one for routine pavement structural analysis, including two 2-D axisymmetric finite-element programs (ILLI-PAVE and MICH-PAVE), one 3-D finite-element program (ABAQUS), and two multilayered elastic-based programs (DAMA and KENLAYER). The most commonly used criteria for pavement design—the maximum surface deflection, tensile (radial) strain at the bottom of the asphalt concrete (AC) layer, and compressive strain at the top of subgrade—were used as the basis for selection. The effects due to treatment of dual-wheel and single-wheel loading and idealization of linear and nonlinear on pavement structure responses were also investigated. For linear and nonlinear analyses, only DAMA and MICH-PAVE satisfy the natural boundary conditions in which the vertical stresses equal the imposed contact pressure of 689 kPa (100 psi). For linear analysis, MICH-PAVE gives the intermediate maximum surface deflection, compressive strain, and tensile strain; for nonlinear analysis, DAMA yields the intermediate maximum surface deflection, compressive strain, and tensile strain. The natural boundary condition is also satisfied in DAMA, and dual-wheel loading can also be considered in computations. The results from ABAQUS yield the lowest tensile strain compared with other programs. The stress-dependant behavior of the material within each layer can be represented using MICH-PAVE and DAMA only when the thickness of the AC layer (h1) is about 22.86 cm (9 in.) or more. The difference between dual-wheel and single-wheel loading is more prominent when h1 is thin (with a maximum difference of 40.5 percent when h1 is 7.62 cm). This suggests that DAMA is probably the most appropriate computer program, among the five computer programs investigated, to use for routine structural analyses of flexible pavements.

More and more flexible pavement designs are being based on a mechanistic approach. In a mechanistic design procedure, a structural analysis tool or computer program is required to predict the stress-strain and displacement response of pavements. A number of computer programs based on the Finite-Element (FE) or the multilayered elasticity (MLE) method have been developed and used for structural analysis of flexible pavement (*1–5*). Overall, the MLE-based procedures are more widely used (*6*) because of their simplicity, but they may suffer from the inability to evaluate the stress-dependant behavior of soil and granular materials and may yield tensile stresses in granular material, which do not occur in the field. In this study, the pavement system is considered a three-layer system, including the subgrade, granular base, and surface asphalt concrete (AC). It is well known that a comprehensive analysis of flexible pavements should include the stress-dependant behavior of granular base course and the cohesive subgrade, the geostatic force of the pavement itself (gravity load), finite width of the AC pavement, multiple wheel loading at any location of the given domain being analyzed, and partial bonding between the AC and the granular layer. However, none of the structural models or computer programs is capable of incorporating all these parameters in analysis simultaneously. Also, the results may vary among analysts because of the assumptions made in each procedure and the different input assigned by individual analysts. Thus, selection of an appropriate computer program for structural analysis of flexible pavements is a challenge for the pavement engineers. A number of structural analysis programs are available, namely, ILLI-PAVE, MICH-PAVE, DAMA, KENLAYER, ABAQUS, CHEVRON, BISAR, ELSYM5, VESYS, and WESLEA (*6*). Of these, the first five programs have been selected to understand better the accuracy and consistency of the structural responses and the results relative to comparison are presented in this paper.

ILLI-PAVE (*5*) developed at the University of Illinois and MICH-PAVE (*3*) developed at the Michigan State University are the two FE computer programs devoted to the structural analysis of flexible pavements capable of accounting for stress-dependant characterization of granular materials and subgrade soils through an iterative scheme. These two programs consider the pavement as an axisymmetric solid of revolution and divide it into a number of finite elements, each as a section of concentric rings. The computer program DAMA (*2*) was developed at the University of Maryland and was used to obtain the structural design charts included in the ninth edition of the Asphalt Institute's MS-1 manual. The nonlinear characterization of granular materials in DAMA was achieved by using an approximate equation that was obtained from a multiple regression analysis. The computer program KENLAYER (*4*) was developed at the University of Kentucky for flexible pavement design and analysis, and and it can be applied to a multilayered system under stationary or moving multiple wheel loads with each pavement layer being either linear elastic, nonlinear elastic, or viscoelastic. ABAQUS, a 3-D finite-element program, has been used successfully in structural analysis of pavement (*7*) and was used in this study to compare and verify its results with those from the 2-D FE programs (ILLI-PAVE and MICH-PAVE) and those from the MLE programs.

OBJECTIVE

The main objective of this study was to identify and select the most appropriate computer program for the routine structural analysis of flexible pavements. The maximum surface deflection, tensile (radial) strain at the bottom of the AC layer, and compressive strain at the top of subgrade are the most commonly used criteria for pave-

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ment design (*4,6,8*) and were used in this study as the basis for selecting the most appropriate computer program. The specific tasks of the study were to:

1. Investigate the differences between linear and nonlinear (i.e., the stress-dependant behavior of soil and granular materials) analyses;
2. Investigate the effect of dual-wheel and single-wheel loading on the structural response of pavements (maximum surface deflection, tensile or radial and compressive strains); and
3. Identify a computer program that is most applicable for analysis of flexible pavements, including the influence of such factors as dual-wheel or single-wheel loading and of stress dependency of the associated materials.

COMPUTER PROGRAMS INVESTIGATED

ILLI-PAVE and MICH-PAVE

In general, the FE methods–based procedures can analyze the nonlinear pavement systems more realistically than other structural models by considering the variation of modulus within each layer (*4*). The stress-dependant properties in the form of resilient modulus (RM) and the failure criteria for granular materials and fine-grained soils were incorporated in ILLI-PAVE (*5*) and MICH-PAVE (*3*). The principal stresses in the granular and subgrade layers are modified at the end of each iteration in a way whereby they do not exceed the strength of the materials, as defined by the Mohr-Coulomb failure envelope. However, the validity of this method for modifying the principal stresses to satisfy the Mohr-Coulomb failure criterion is questionable (*4*). Because the stresses in one element are adjusted in this algorithm, they must be redistributed to the adjoining elements. Thus, the adjusted stresses in each element without considering the overall equilibrium do not appear to be theoretically correct (*4*). Another limitation of ILLI-PAVE and MICH-PAVE is the representation of wheel loading by a single interior circular area in which dual-wheel and edge loading cannot be taken into account. Although the actual contact area is not circular, the circular loaded area was assumed to enable the axisymmetric idealization in ILLI-PAVE and MICH-PAVE.

ILLI-PAVE and MICH-PAVE use the same method to characterize granular materials and fine-grained soils and the same Mohr-Coulomb failure criterion to adjust the state of stresses. A major difference between ILLI-PAVE and MICH-PAVE is that MICH-PAVE uses a flexible boundary at a limited depth beneath the subgrade instead of a rigid boundary at a greater depth (50 times the radius of the applied load) below the subgrade. The flexible boundary, which accounts for displacements that occur beneath it, enables the bottom boundary to be placed at any depth below which displacements and stresses are of no interest. The use of the flexible boundary greatly reduces the number of degrees of freedom (DOF) required and thus reduces the computation time. The half-space below the flexible boundary is assumed to be homogeneous and linear elastic. To account for the coupling between the flexible boundary and the finite elements, the stiffness matrix of the half-space, which corresponds to the DOF along the boundary, is obtained from the inverse of the flexibility matrix because of its simplicity (*3*). The radial boundaries of ILLI-PAVE and MICH-PAVE are located at a distance of 12 times and 10 times the radius of the applied load, respectively.

Nonlinear Analysis in MICH-PAVE and ILLI-PAVE

To determine the stresses, strains, and deflections in the pavement system, it is necessary to have a proper constitutive model to address the stress-dependant behavior of granular materials and the subgrade soils. The stress-dependant characteristics of untreated granular materials in Equation 1 is most commonly used by researchers (*4,9–12*), and it is used in MICH-PAVE and ILLI-PAVE. However, it should be noted that one drawback of this model is that the stress path is limited in which the material constants were derived through laboratory compressive stress tests that do not cover an adequate range of stress paths encountered in the field. Brown and Pappin (*13*) also reported that the K-θ model in Equation 1 has been found to fit the laboratory shear strain data well, but it does not handle the volumetric strains properly.

$$RM_2 = K_1\theta^{K_2} \tag{1}$$

where K_1 and K_2 are two material constants determined from laboratory testing. The ranges of K_1 and K_2 are well documented (*11,12*). The model is also discussed in the report by Laguros et al. (*9*), who investigated six types of aggregates by using the testing procedures T294-92I and T292-91I suggested by AASHTO in 1991 (*14*) and 1992 (*15*), respectively.

For a cohesive subgrade soil, the RM is expressed through a bilinear relationship, as given in Equations 2 and 3.

for $K_1 > (\sigma_1 - \sigma_3)$

$$RM_3 = K_2 + K_3\,[K_1 - \sigma_1 + \sigma_3] \tag{2}$$

and for $K_1 < (\sigma_1 - \sigma_3)$

$$RM_3 = K_2 + K_4[\sigma_1 - \sigma_3 - K_1] \tag{3}$$

in which K_1, K_2, K_3, and K_4 are material constants.

Abaqus

ABAQUS, a 3-D FE program (*1*), has been used successfully in structural analysis of pavement (*7*) and was used here to provide a more realistic representation of a pavement system and to verify the FE programs based on an axisymmetric idealization and the MLE-based programs. An attempt was made to find the difference between the results obtained from the 3-D analysis and those from 2-D FE and MLE programs and to investigate whether the 3-D FE analyses are necessary or even beneficial in the routine design. The 3-D infinite element was used in the vertical direction to reduce the number of elements required in the idealization and thus reduce the computation time. The infinite element was located 152.4 cm below the pavement surface. An example of the mesh used in this study is shown in Figure 1. The mesh presented in Figure 1 has 3,825 nodes and 3,072 elements. The computing time was approximately 1 to 2 hr for a VAX 6520-VMX machine at the University of Oklahoma, not including preparation of input data. In the present study, the geostatic forces due to self-weight were considered and the material models for the granular base and the subgrade layer were assumed to be linear elastic. Also, the equivalent area concept was

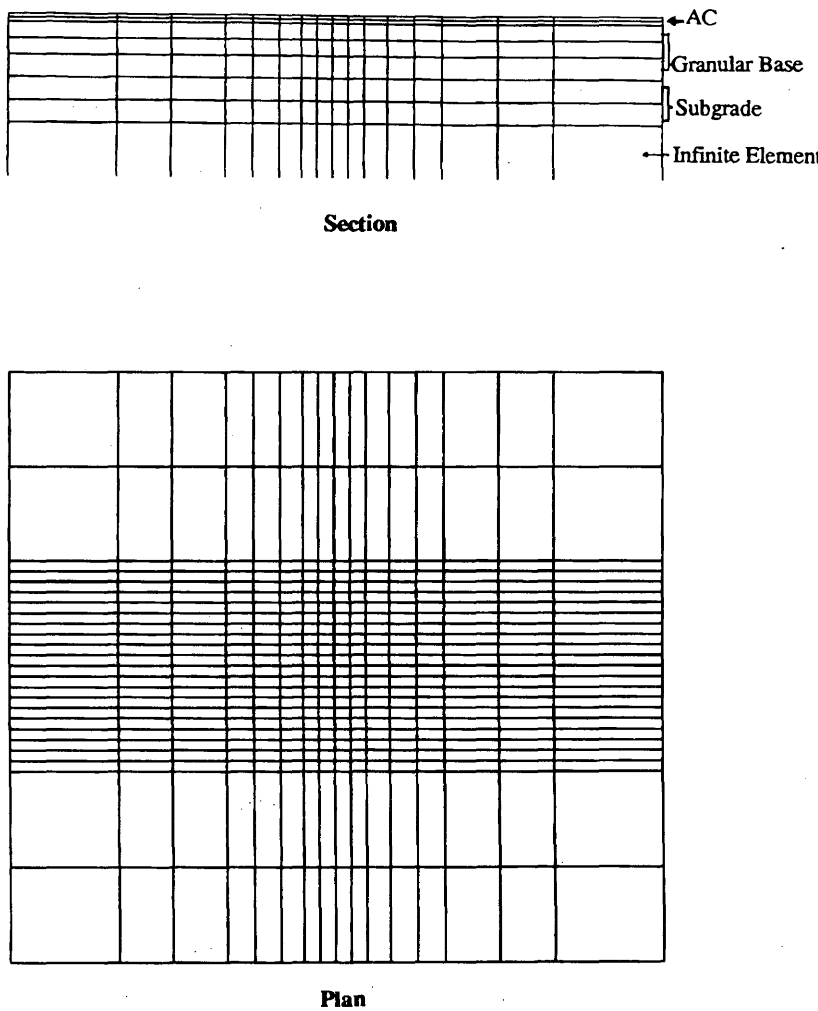

FIGURE 1 Typical FE mesh for ABAQUS.

used to obtain the rectangular loaded area for ABAQUS. For example, a 40.45-kN single loaded radius of 13.589 cm, with a 689-kPa contact pressure, is equivalent to the rectangular loaded area of 29.03 × 20 cm having the same contact pressure of 689 kPa.

MLE Model

MLE- and FE-based models are used extensively in flexible pavement analysis procedures. Overall, the MLE-based procedures are more widely used (*6*). The historical development and general description of various MLEs can be found elsewhere (*3,8*). However, in general, the MLE programs have the following drawbacks:

- They could not model the nonlinear resilient behavior of granular and cohesive soils in a realistic manner.
- The layers are in full contact.
- They may yield tensile stresses in a granular material, which do not occur in the field.

DAMA

The computer program DAMA (*2*) was developed at the University of Maryland for developing the structural design charts used in the ninth edition of the Asphalt Institute's MS-1 manual (*16*). DAMA is an elastic-layered pavement analysis program that can be used to analyze a multilayered elastic pavement structure by cumulative damage techniques induced by single- or dual-wheel loading.

Nonlinear Analysis in DAMA

In DAMA, the subgrade and AC layers are considered linear elastic and the untreated granular base nonlinear elastic. Considering the subgrade a linear elastic material is a reasonable approximation because the variation of modulus from the change of subgrade stresses is usually small and a reasonable subgrade modulus can be assumed. Instead of using a more accurate method of iterations to determine the RM of the granular layer, the following predictive

TABLE 1 Case Study

RM Values	h1=3"	h1=6"	h1=9"
RM1 =250 ksi	Case 1	Case 2	Case 3
RM1 =500 ksi	Case 4	Case 5	Case 6
RM1 =750 ksi	Case 7	Case 8	Case 9

inch = " = 2.54 cm

equation based on multiple regression is used to account for stress dependency (*2,17*):

$$RM_2 = 10.447h_1^{-0.471}h_2^{-0.041}RM_1^{-0.139}RM_3^{0.287}K_1^{0.868} \quad (4)$$

where

RM_1, RM_2, and RM_3 = moduli of the asphalt layer, granular base, and subgrade, respectively;
h_1 and h_2 = thickness of the asphalt layer and the granular base, respectively; and
K_1 = nonlinear constant in Equation 1 with the exponent K_2 equal to 0.5.

KENLAYER

KENLAYER (*4*) treats the flexible pavement structure as an elastic multilayer system under a circular loaded area. For multiple wheels, the superposition principle is applied directly in KENLAYER for a linear system. In a nonlinear elastic system, the superposition principle is also applied but with a method of successive approximations. First, the system is considered linear, and the stresses due to multiple-wheel loads are superimposed. Based on the stresses computed, a new modulus is determined. Then, the system is considered linear again, and the process is repeated until the modulus converges to a specified tolerance.

Nonlinear Analysis in KENLAYER

Two methods can be applied in KENLAYER to account for the nonlinearity in the granular layers (*4*). In Method 1, the nonlinear granular layer is subdivided into a number of layers and the stresses at the middepth of each layer are used to determine RM. If the horizontal stress, including the geostatic stress, is negative, it is set to zero. This modification helps avoid negative bulk stress. In Method 2, the layers of granular materials are considered a single layer and a point, normally between the upper quarter and the upper third of the layer, and they are selected to compute the RM.

KENLAYER uses the stresses at a single point in each nonlinear layer to compute the modulus of the layer, which is not theoretically correct. As the stresses vary with the radial distance from the load, the modulus should also change with the radial distance and is not uniform throughout the layer. It is important to note that even in nonlinear analysis, both DAMA and KENLAYER consider each horizontal layer having a constant modulus material. However, in the nonlinear analysis in ILLI-PAVE and MICH-PAVE, the moduli vary with elements even for the same horizontal layer.

CASE STUDY

By varying the thickness of the AC layer (h1) and its modulus (RM1), while keeping the thickness and properties of the other layers constant, it is possible to identify a matrix of nine different cases, as given in Table 1. In practice, it is rare to have AC thickness less than 7.62 cm. Also, the effect on the structural response from the variation of the thickness of the granular base layer (h2) and its modulus (RM2) is found to be minimum (*4*). Therefore, they were not included. The material properties used in this case study are presented in Table 2 and Figure 2.

Current FE methodology has advantages over layered-elastic solutions because it provides greater flexibility in realistically modeling the nonlinear response characteristics of granular base layer and subgrade soil. The use of MLE programs and the ILLI-PAVE finite-element program for the development of future AASHTO design guides was recommended (*6*). It was suggested to use the modulus-depth relationship obtained from ILLI-PAVE to establish the various moduli for the MLE, thus capitalizing on the stress-dependent feature of the ILLI-PAVE and the multiple-wheel capability of MLE (*6*). However, in general, the results from MICH-PAVE are more accurate and realistic than those from the ILLI-PAVE because of MICH-PAVE's use of a flexible boundary as apposed to the rigid boundary in ILLI-PAVE (*4*). Furthermore, a study by Harichandran et al. (*18*) found the use of an equivalent layer resilient modulus (ELRM) (obtained from MICH-PAVE) for each layer by averaging the moduli of the finite elements in the layer that lie within an assumed 2:1 load distribution zone can be adequately used to reflect the stress-dependent variation of the modulus within the layer. Hence, MICH-PAVE was

TABLE 2 Material Constants Used

Layer	Poisson's ratio	Unit Weight (pcf)	k0	k1	k2	k3	k4	C (psi)	ϕ (degree)
AC	0.35	150	0.7						
Base	0.38	140	0.6	5000	0.5			0	45
Soil	0.45	115	0.8	5.2	3021	1110	-178	6	0

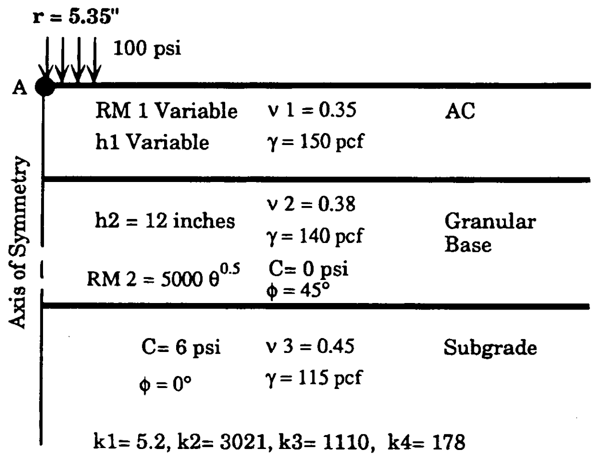

FIGURE 2 Problem description (single wheel).

selected in this study to compute ELRM. The computed ELRM for the aforementioned nine cases are given in Table 3, wherein the values were obtained by fixing the flexible boundary at 114.3 cm below the surface of the subgrade soil. Harichandran et al. (*3*) recommended that the position for flexible boundary is at least 91. 44 cm below the surface of the subgrade soil. The ELRMs for subgrade soil are the same (60 MPa or 8,694 psi), indicating that treating the subgrade as a linear elastic medium is a fair assumption.

COMPARISON OF RESULTS FOR LINEAR ANALYSIS

Contact Stress (Natural Boundary Condition)

For linear analysis, a comparison of vertical stress obtained from different computer programs at Point A in Figure 2 is presented in Table 4. The ELRM values obtained from MICH-PAVE, as given in Table 3, were used as the moduli in the granular layer and subgrade soil. From Table 4, it can be inferred that only DAMA and MICH-PAVE satisfy the natural boundary condition in which the vertical stresses equal the imposed contact pressure 689 kPa (100 psi).

Maximum Surface Deflection, Tensile Strain, and Compressive Strain

A comparison of the maximum surface deflection, tensile (radial) strain at the bottom of the AC layer and compressive strain at the top of the subgrade soil obtained from different computer programs is illustrated in Table 5A, B, and C. It was reported that the conventional analyses may overestimate the tensile (radial) strain at the bottom of AC layer when comparing it with 3-D linear elastic FE analysis (*19*). This phenomenon is confirmed in this study. In fact, even the 2-D axisymmetric FE models (ILLI-PAVE and MICH-PAVE) overestimate the tensile (radial) strain at the bottom of the AC layer. Examination of Table 5A, B, and C indicates the following:

- In all cases, ILLI-PAVE gave the lowest maximum surface deflection due to the fixed boundary at a certain depth.
- In most cases (seven out of nine), KENLAYER yielded the highest maximum surface deflections.
- In all cases, ABAQUS gave the lowest tensile strain.
- In all cases, the tensile strains obtained from DAMA and KENLAYER had close agreement, and the latter gave the highest tensile strain.
- In all cases, DAMA provided the highest compressive strain.
- In all cases, the maximum surface deflections obtained from ABAQUS had a close agreement with those obtained from MICH-PAVE.
- The variability of tensile strain was lower than that in compressive strain.

TABLE 3 ELRM from MICH-PAVE for Cases 1 to 9

Layer	ELRM h1=3" (psi)	ELRM h1=6" (psi)	ELRM h1=9" (psi)
Case	(1)	(2)	(3)
AC	250000	250000	250000
Base	25630	17464	13745
Soil	8694	8694	8694
Case	(4)	(5)	(6)
AC	500000	500000	500000
Base	23317	14770	12860
Soil	8694	8694	8694
Case	(7)	(8)	(9)
AC	750000	750000	750000
Base	21598	13922	12462
Soil	8694	8694	8694

1 psi = 6.89 kPa; inch = 2.54 cm

TABLE 4 Comparison of Vertical (Compressive) Stresses of Figure 2 by Using Linear Analysis

Cases	Programs	Vertical Stress (psi)
	DAMA	100
	ILLIPAVE	87
Case 4	KENLAYER	140
	MICHPAVE	100
	ABAQUS	57
	DAMA	100
	ILLIPAVE	91
Case 5	KENLAYER	100
	MICHPAVE	100
	ABAQUS	61
	DAMA	100
	ILLIPAVE	98
Case 6	KENLAYER	74
	MICHPAVE	100
	ABAQUS	62

1 psi = 6.89 kPa

TABLE 5 Comparison [by Using Nonlinear (NL) and Linear (L) Analysis] of Maximum Surface Deflections (milli in.) at Axis of Symmetry (*top*), Compressive Strains (microstrain) at Top of Subgrade (*middle*), and Tensile (Radial) Strains (microstrain) at Bottom of AC Layer (*bottom*)

		DAMA		ILLI		KENL		MICH		ABAQ
RM1	h1	NL	L	NL	L	NL	L	NL	L	L
250	3"	37.69	35.35	42.93	29.98	42.56	35.79	38.11	33.58	32.90
(ksi)	6"	27.84	27.16	27.67	21.96	39.26	27.41	26.87	25.39	26.28
	9"	21.55	21.38	20.41	16.96	26.67	21.70	20.24	19.98	21.00
500	3"	34.58	32.95	36.58	26.57	38.31	32.91	34.28	30.57	29.50
(ksi)	6"	23.30	19.08	21.57	17.59	30.29	23.12	21.74	21.24	21.92
	9"	17.13	15.46	15.60	12.79	20.09	16.81	16.05	16.05	16.29
750	3"	32.48	31.08	32.43	24.35	35.48	31.16	31.64	28.68	27.54
(ksi)	6"	20.84	20.76	18.51	15.13	26.34	20.56	19.14	18.83	19.29
	9"	14.99	14.84	13.52	10.91	17.21	14.79	14.41	14.33	13.93

		DAMA		ILLI		KENL		MICH		ABAQ
RM1	h1	NL	L	NL	L	NL	L	NL	L	L
250	3"	1004	954	1334	757	828	698	944	783	663
(ksi)	6"	587	582	623	451	623	478	507	465	464
	9"	359	360	343	279	275	326	274	269	311
500	3"	902	868	1034	660	745	651	815	699	603
(ksi)	6"	452	406	418	332	460	397	356	344	372
	9"	250	256	211	188	261	242	178	177	226
750	3"	825	804	867	589	676	617	721	638	560
(ksi)	6"	377	377	317	266	384	341	280	275	310
	9"	197	200	164	145	211	198	136	134	182

		DAMA		ILLI		KENL		MICH		ABAQ
RM1	h1	NL	L	NL	L	NL	L	NL	L	L
250	3"	604	543	537	502	622	543	489	527	351
(ksi)	6"	418	404	394	366	464	404	370	367	280
	9"	262	259	249	239	369	258	225	224	185
500	3"	481	445	442	399	484	444	416	423	286
(ksi)	6"	275	207	252	240	291	272	243	241	184
	9"	161	137	147	143	165	158	132	132	117
750	3"	400	378	368	333	395	378	358	357	214
(ksi)	6"	207	207	186	178	218	206	181	180	138
	9"	118	116	104	102	121	117	94	94	81

- As h1 and RM1 increased, the difference in maximum surface deflections, tensile strains, and compressive strains among the programs decreased.
- Among all programs investigated in this study, the MICH-PAVE gave the intermediate maximum surface values for deflection, compressive strain, and tensile strain.

Deflection Profile

The surface deflection profiles for Cases 4, 5, and 6, respectively, are given in Figure 3. It was observed that ILLI-PAVE gives the lowest surface deflection along the radial direction. MICH-PAVE and ABAQUS provided the closest deflection profiles for all three

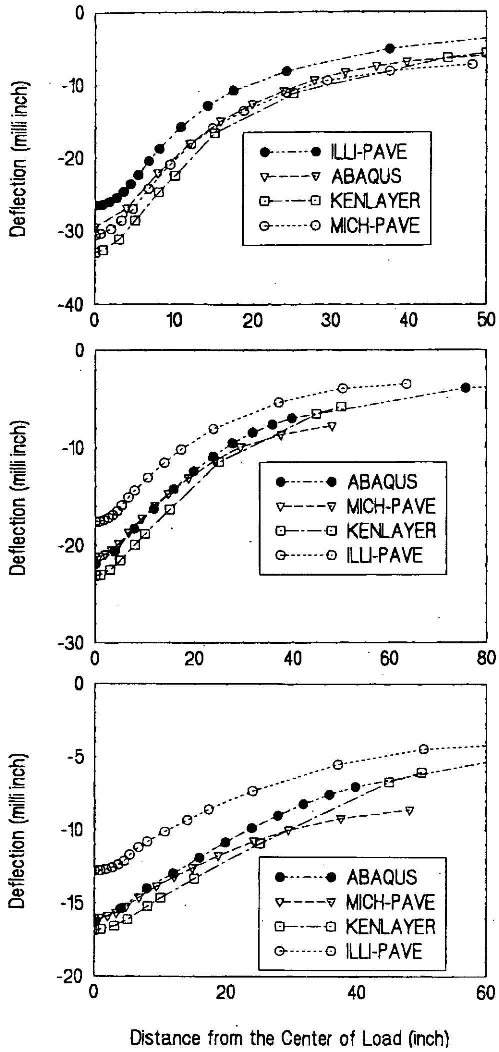

FIGURE 3 **Comparison of surface deflection profiles from various computer programs for L analysis: Case 4—RM1 = 500 ksi, h1 = 3 in. (*top*); Case 5—RM1 = 500 ksi, h1 = 6 in. (*middle*); Case 6—RM1 = 500 ksi, h1 = 9 in. (*bottom*).**

cases investigated. The computer program DAMA did not give the deflection along a radial direction; consequently, it was not included in the comparison.

COMPARISON OF RESULTS FOR NONLINEAR ANALYSES

Contact Stress (Natural Boundary Condition)

Similar to linear analysis, only DAMA and MICH-PAVE satisfy the natural boundary conditions in which the vertical stresses equal the imposed contact pressure of 689 kPa, as shown in Table 6. Note that in the present study, linear elastic idealization was used in ABAQUS's analysis and thus it was not included in the comparison.

TABLE 6 **Comparison of Vertical (Compressive) Stresses at Point A of Figure 2 by Using NL Analysis**

Cases	Programs	Vertical Stress (psi)
Case 4	DAMA	100
	ILLIPAVE	89
	KENLAYER	130
	MICHPAVE	100
Case 5	DAMA	100
	ILLIPAVE	91
	KENLAYER	74
	MICHPAVE	100
Case 6	DAMA	100
	ILLIPAVE	98
	KENLAYER	74
	MICHPAVE	100

1 psi = 6.89 kPa

Maximum Surface Deflection, Tensile Strain, and Compressive Strain

The maximum surface deflection, tensile (radial) strain at the bottom of the AC layer, and compressive strain at the top of the subgrade from different computer programs for nonlinear analyses are compared in Table 5, indicating a wide dissimilarity in results obtained from these programs. In view of Table 5, the following observations are made:

- In most cases (eight out of nine), KENLAYER gave the highest maximum surface deflections.
- In most cases (eight out of nine), the maximum surface deflections from DAMA, ILLI-PAVE, and MICH-PAVE had a close agreement.
- In all cases, the compressive strains from DAMA and ILLI-PAVE had a close agreement, and DAMA gave higher values compared with MICH-PAVE.
- In all cases, KENLAYER yielded the highest tensile strain.
- In all cases, MICH-PAVE gave the lowest tensile strain.
- Among all programs investigated in this study, DAMA provided the intermediate maximum surface deflections and compressive and tensile strains.

COMPARISON OF LINEAR AND NONLINEAR ANALYSIS

Comparison of Maximum Surface Deflection, Tensile Strains, and Compressive Strains Between Linear and Nonlinear Analyses in MICH-PAVE

It is noteworthy to identify the differences between the results obtained from the nonlinear analysis and those from the linear analysis (using the ELRM computed from nonlinear analysis) using the same computer program (MICH-PAVE). A comparison of maximum surface deflection, compressive strain at the bottom of the AC layer, and tensile (radial) strain at the top of the subgrade is presented in Table 7. The differences between nonlinear and linear

TABLE 7 Comparison of Maximum Surface Deflections, Tensile (Radial) Strains at Bottom of AC Layer, and Compressive Strains at Top of Subgrade for MICH-PAVE by Using NL and L Analysis

Cases	Conditions	DEF. (milli inch)	C (microstrain)	T
Case 1	Nonlinear	38.11	944	489
	Linear	33.58	783	527
	Difference (%)	13.5	20.6	7.2
Case 2	Nonlinear	26.87	507	370
	Linear	25.39	465	367
	Difference (%)	5.8	9.0	0.8
Case 3	Nonlinear	20.24	274	225
	Linear	19.98	269	224
	Difference (%)	1.3	1.9	0.4
Case 4	Nonlinear	34.28	815	416
	Linear	30.57	699	423
	Difference (%)	13.1	16.6	1.7
Case 5	Nonlinear	21.74	356	243
	Linear	21.24	344	241
	Difference (%)	2.4	3.5	0.8
Case 6	Nonlinear	16.16	178	132
	Linear	16.05	177	132
	Difference (%)	0.7	0.6	0
Case 7	Nonlinear	31.64	721	358
	Linear	28.68	638	357
	Difference (%)	10.3	13.0	0.3
Case 8	Nonlinear	19.14	280	181
	Linear	18.83	275	180
	Difference (%)	1.6	1.8	0.6
Case 9	Nonlinear	14.41	136	94
	Linear	14.33	134	94
	Difference (%)	0.6	1.5	0

inch = 2.54 cm

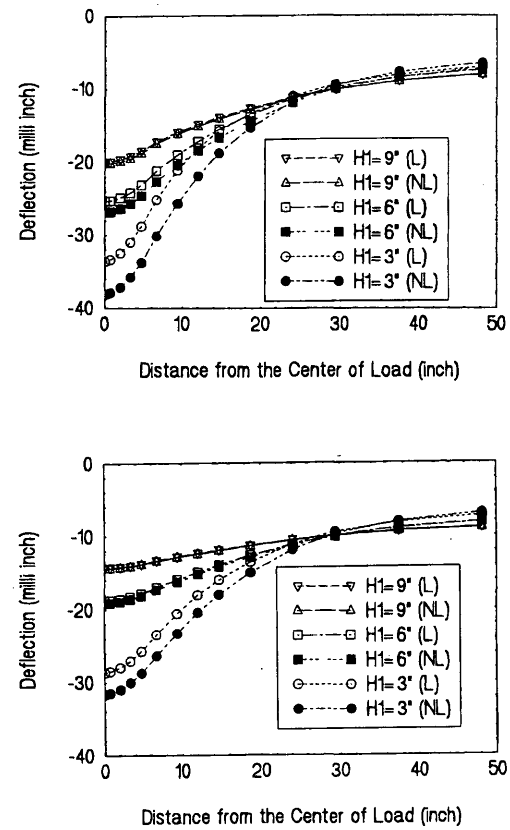

FIGURE 4 Comparison of surface deflection profiles between NL and L analysis from MICH-PAVE: Cases 1 to 3—RM1 = 250 ksi, h1 = 3, 6, 9 in. (*top*); Cases 7 to 9—RM1 = 750 ksi, h1 = 3, 6, 9 in. (*bottom*).

analysis are also given in this table. Table 7 illustrates that, as RM1 and h1 increases, the difference between the results from the nonlinear and linear analyses decreases. The maximum difference of 20.6 percent for compressive strains for Case 1 (h1 = 7.62 cm) indicates that the ELRM could be used satisfactorily to represent the stress-dependant behavior of the materials within each layer. Because the stress-dependant behavior of granular base and subgrade soil could be approximated by the use of ELRM, it may also be approximated by Equation 4. This explains why the results for nonlinear analysis from DAMA, MICH-PAVE, and ILLI-PAVE had a close agreement.

Comparison of Surface Deflection Profile Between Linear and Nonlinear Analyses by MICH-PAVE

The surface deflection profiles for the nine cases, using the MICH-PAVE for nonlinear analysis and linear analysis, were obtained and are presented in Figure 4. In view of these figures, a similar trend is observed for the surface deflection profiles and those for maximum surface deflection and tensile and compressive strains (i.e., as RM1 and h1 increase, the difference between nonlinear and linear analysis decreases, as expected).

Comparison of Surface Deflection Profile Between Linear and Nonlinear Analysis

The surface deflection profiles obtained from the linear analysis using ILLI-PAVE, ABAQUS, and MICH-PAVE and from the nonlinear analysis using ILLI-PAVE and MICH-PAVE were grouped and are presented in Figure 5. Only Cases 4, 5, and 6 were investigated here because an AC modulus of 3 445 MPa (500 ksi) is most commonly used in design, and the effect of AC thickness on the structural response is more significant than the effect due to the AC modulus. It was observed that as h1 increases, the difference in the deflection based on ABAQUS (linear), MICH-PAVE (linear and nonlinear), and ILLI-PAVE (nonlinear) decreases. In fact, the surface deflection profiles for ABAQUS (linear) and MICH-PAVE (linear and nonlinear) for Case 6 are approximately the same [Figure 5 (*bottom*)], indicating that when h1 is thick (22.86 cm = 9 in.) the nonlinear behavior is less dominant. This observation

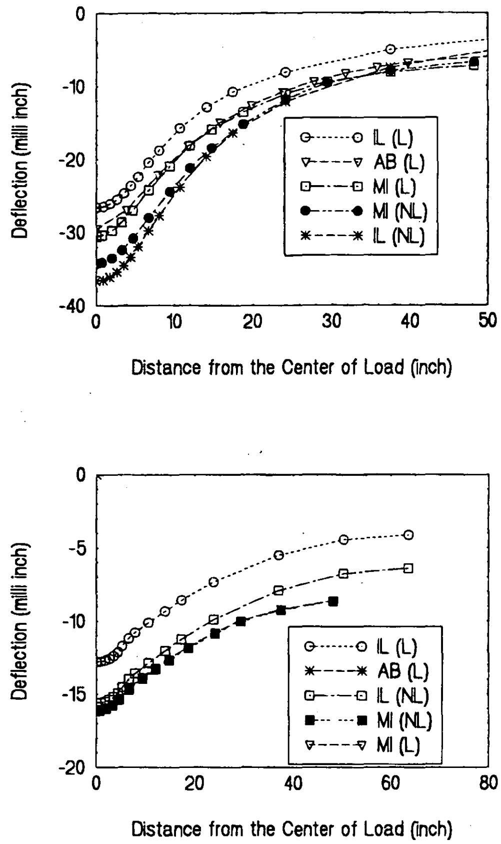

FIGURE 5 Comparison of surface deflection profiles between NL and L analysis among programs: Case 4—RM1 = 500 ksi, h1 = 3 in. (*top*); Case 6—RM1 = 500 ksi, h1 = 9 in. (*bottom*).

supports the use of the ELRM concept in MICH-PAVE for satisfactorily computing the surface deflections.

Comparison of Maximum Surface Deflection, Tensile Strain, and Compressive Strain Between Linear and Nonlinear Analyses

A comparison of nonlinear and linear analyses for maximum surface deflection, tensile strain, and compressive strain is presented in Table 5. A close examination of the results presented indicates the following:

- By using the same program, as h1 and RM1 increase, the difference between the linear and the nonlinear analysis decreases.
- For both the nonlinear and linear analyses, as h1 and RM1 increase, the difference in results obtained from the different programs decreases.
- As expected, the nonlinear analysis gave higher values of maximum surface deflection, tensile strain, and compressive strain than those from linear analysis.
- In terms of increment ratios, to reduce the level of maximum surface deflection, tensile strain, and compressive strain more effectively is to increase the thickness of h1 than to increase the modulus of RM1.

DUAL WHEEL VERSUS SINGLE WHEEL

The three programs—ABAQUS, DAMA, and KENLAYER—investigated in this study can consider the effect of dual wheel on the pavement structure, as shown in Figure 6. The moduli of granular layer and subgrade are the ELRM values obtained from MICH-PAVE, as given in Table 3. The comparison of dual-wheel linear analysis among these three programs is presented in Table 8 and the following observations are made:

- In all three cases, ABAQUS gave the lowest tensile strain.
- In all three cases, DAMA provided the lowest compressive strain.
- In all three cases, DAMA yielded the lowest and KENLAYER gave the highest maximum surface deflection, respectively.
- DAMA gave the intermediate tensile strains.

Because DAMA gave the intermediate surface deflection, compressive strain, and tensile strain in the nonlinear analysis, it was decided to study the difference in results for the single-wheel and dual-wheel idealization for both the linear and nonlinear analyses. The differences between the single-wheel nonlinear and the dual-wheel nonlinear analysis were computed and are given in Table 9. The following observations are made:

- Single-wheel nonlinear analysis gave the highest maximum surface deflection and compressive and tensile strains.
- Dual-wheel linear analysis gave the lowest maximum surface deflection and compressive and tensile strains.
- As h1 increases, the difference between single-wheel nonlinear and dual-wheel nonlinear analysis decreases for both the maximum surface deflection and compressive strain but not for the tensile strain.
- A maximum difference of 40.5 percent in compressive strain was observed between the single-wheel and dual-wheel nonlinear analyses, when h1 was equal to 3 in.

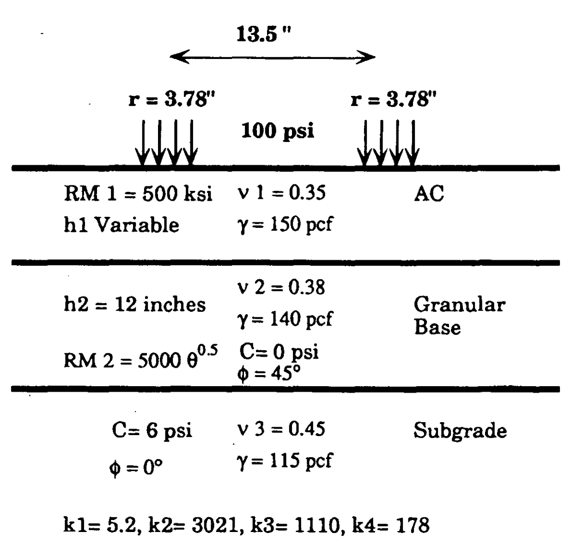

FIGURE 6 Problem description (dual wheel).

TABLE 8 Comparison of Maximum Surface Deflections at Center of Dual Wheel, Tensile (Radial) Strains at Bottom of AC Layer, and Compressive Strains at Top of Subgrade by Using L Analysis

Cases	Programs	DEF. (milli inch)	C (microstrain)	T
Case 4	DAMA	18.38	383	183
	KENLAYER	26.76	513	296
	ABAQUS	23.38	484	175
Case 5	DAMA	17.2	320	166
	KENLAYER	20.78	350	212
	ABAQUS	19.61	335	128
Case 6	DAMA	14.53	215	111
	KENLAYER	15.67	222	133
	ABAQUS	14.85	210	84

inch = 2.54 cm

ASSESSMENT OF NUMBER OF VARIABLES AND TESTING TIME

Some of the variables in the programs may be used only for certain problems. For example, KENLAYER can consider, among others, multiple wheel loads and viscoelastic analysis. Thus, when comparing programs it is better to consider the number of variables required as input for the same problem. The same problem in Figure 2 was selected for this purpose. Table 10 shows a comparison of the number of variables required as input for the five programs investigated. It was observed that DAMA required the least input variables, followed by MICH-PAVE, and ABAQUS needed the most input variables.

To compare the running time for the computer programs considered, an example (Case 4, RM1 = 3445 MPa, h1 = 7.62 cm) was used. The approximate time to run this example is shown in Table 10. A 386 PC (25 MHz) with a math coprocessor was used in this study (except for ABAQUS). Note that the input preparation time was not included and only the running time is given in Table 10. The data in Table 10 show that the running time for KENLAYER is the least, followed by MICH-PAVE, and the 3-D FE general-purpose program ABAQUS required maximum time, as expected.

CONCLUSIONS

Two 2-D axisymmetric FE programs (ILLI-PAVE and MICH-PAVE), one 3-D FE program (ABAQUS), and two multilayered elastic-based programs (DAMA and KENLAYER) were reviewed, evaluated, and compared in this study. The contact stress (nature boundary condition), maximum surface deflection, tensile (radial) strain, and compressive strain were used as the evaluation criteria. The effects from treatment of dual-wheel and single-wheel loading and linear and nonlinear idealization on pavement structure responses were investigated. From the analysis of the results presented in the preceding sections, the following observations and conclusions were made:

- For both linear and nonlinear analyses, only DAMA and MICH-PAVE satisfied the natural boundary condition in which the vertical stresses equal the imposed contact pressure of 689 kPa.
- For linear analysis, MICH-PAVE gave the intermediate maximum surface deflection, compressive strain, and tensile strain.
- For linear analysis, ABAQUS gave the lowest tensile strain, as reported in the literature.

TABLE 9 Comparison of Single and Dual Wheel for DAMA by Using L and NL Analysis

Cases	Programs	DEF. (milli inch)	C (microstrain)	T
Case 4	Single-wheel (L)	32.95	868	445
	Dual-wheel (L)	18.38	383	183
	Single-wheel (NL)	34.58	902	481
	Dual-wheel (NL)	27.89	642	402
	difference* (%)	**24.0**	**40.5**	**19.7**
Case 5	Single-wheel (L)	19.08	406	207
	Dual-wheel (L)	17.2	320	166
	Single-wheel (NL)	23.3	452	275
	Dual-wheel (NL)	20.59	360	222
	difference (%)	**13.16**	**25.6**	**23.9**
Case 6	Single-wheel (L)	15.46	256	137
	Dual-wheel (L)	14.53	215	111
	Single-wheel (NL)	17.13	250	161
	Dual-wheel (NL)	16.0	210	130
	difference (%)	**7.1**	**19.0**	**23.8**

inch = 2.54 cm

*

The computed differences were the differences between Single-wheel (NL) and Dual-wheel (NL)

TABLE 10 Comparison of Number of Variables Required as Input and Testing Time

Program	DAMA	ILLI-PAVE	KENLAYER	MICH-PAVE	ABAQUS
Vaiables	20	34	47	29	more than 50
Running Time	36 Sec. 386 PC	332 Sec. 386 PC	21 Sec. 386 PC	33 Sec. 386 PC	519 Sec. (CPU time for VAX6520 Computer)

• The surface profiles from ABAQUS and MICH-PAVE had a close agreement.

• For nonlinear analysis, DAMA gave the intermediate maximum surface deflections and compressive and tensile strains.

• As h1 and RM1 increase, the difference in results between linear and nonlinear analyses decreases.

• When h1 is thick [22.86 cm (9 in.)], ELRMs from MICH-PAVE and Equation 4 in DAMA were used satisfactorily to represent stress-dependent behavior of the materials within each layer.

• The results from the 3-D FE program ABAQUS indicate that the surface profiles from ABAQUS and the 2-D axisymmetric FE program MICH-PAVE had a close agreement, but the results from ABAQUS yield the lowest tensile strain compared with other programs. Also, the computing time is approximately 1 to 2 hr for a VAX 6520-VMX machine. Thus, for a thin AC section, ABAQUS may be used for verification purpose but not for routine pavement structural analysis.

• In terms of increment ratios, to reduce the level of maximum surface deflection, tensile strain, and compressive strain more effectively, it is necessary to increase the thickness of h1 instead of RM1.

• The dual-wheel loading always gave less maximum surface deflection, tensile strain, and compressive strain than those obtained from single-wheel loading.

• The maximum difference between single-wheel and dual-wheel analyses was found to be 40.5 percent when h1 is 7.62 cm (3 in.). As h1 increases, the difference in results between single-wheel and dual-wheel analyses decreases.

• Because DAMA gave the intermediate maximum surface deflection, compressive strain, and tensile strain in nonlinear analysis; satisfied the natural boundary condition; required the least input variables; and has the capacity to consider dual-wheel loading, it suggests that DAMA is probably the best one to use in routine pavement design.

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