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ASSESSMENT OF LINEAR AND NON-LINEAR ANALYSES OF FLEXIBLE PAVEMENT

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ABSTRACT

Two computer programs were reviewed and evaluated, one for linear analysis (LA) and the other for non-linear analysis (NLA), to identify the most appropriate analysis type for flexible pavement structural analysis. The programs were three-dimensional (3-D) finite element (FE) programs called SAP90 and ANSYS5.3. The comparison items were the maximum surface deflection, the maximum vertical compressive strain at the top of the subgrade and the maximum horizontal tensile strain at the bottom of the asphalt concrete (AC) layer, which are the most commonly used criteria for pavement design. In addition to these items, maximum tensile stress in AC layer and vertical stress distribution along the pavement depth were used as the basis for comparison. Three load conditions include horizontal forces (HF) were applied to the flexible pavement models. Non-linear analysis was found to be more realistic for flexible pavement analysis. It satisfied the surface boundary condition and gave more acceptable results when studying shoving and vertical stress distribution under loading center.

KEY WORDS

Structural Analysis, Highways, Flexible Pavements, and Finite Elements.

NOMENCLATURE

LA	Linear analysis.
NLA	Non-linear analysis.
3-D	Three dimensional.
FE	Finite element.
AC	Asphalt concrete.
MLE	Multilayered elasticity.
h_1	Asphalt concrete layer thickness.

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h_2	Untreated base layer thickness.
h_3	Subgrade layer thickness.
ν_1	Poisson's ratio for the asphalt concrete layer.
ν_2	Poisson's ratio for the untreated base layer.
ν_3	Poisson's ratio for the subgrade layer.
E_1	Modulus of elasticity for the asphalt concrete layer.
E_2	Modulus of elasticity for the untreated base layer.
E_3	Modulus of elasticity for the subgrade layer.
f_t	Tensile strength.
f_c	Compressive strength.
VWL	Vertical wheel load.
HF	Horizontal force.
μ	Coefficient of road adhesion.
μ_p	Peak value of the coefficient of road adhesion.
LONGF	Longitudinal force.
LATF	Lateral force.
ε_c	Maximum Vertical compressive strain at the top of the subgrade layer.
ε_t	Maximum horizontal tensile strain at the bottom of the asphalt concrete layer.
$\sigma_{t\,max}$	Maximum tensile stress in asphalt concrete layer.

INTRODUCTION

More and more flexible pavement designs are being based on a mechanistic approach. In a mechanistic design procedure, structural analysis tools or computer programs are required to predict the stress-strain and displacement response of pavements. A number of computer programs based on the FE or the multilayered elasticity (MLE) method have been developed and used for structural analysis of flexible pavement. Overall, the MLE-based procedures are more widely used because of their simplicity, but they may suffer from the inability to evaluate the stress-dependent behavior of soils and granular materials and may yield tensile stresses in granular material, which do not occur in the field. It is well known that a comprehensive analysis of flexible pavements should include the stress-dependent behavior of granular base, subgrade material, and AC layer. However, none of the structural models or computer programs is capable of incorporating all these parameters in analysis simultaneously [1]. 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. On the other hand, material properties required for NLA may differ from that for LA. Thus, the selection of analysis type to be linear or non-linear analysis affects to a large extent the results of analysis.

For the design procedure of pavement to be completely rational in nature, the analysis type should represent the material properties for each pavement layer. The main objective of this study was to identify and select the appropriate analysis type to be linear or non-linear for the structural analysis of flexible pavements. This was accomplished by studying the response of flexible pavements using linear and non-linear analyses. Theoretical analysis, using FE technique, of flexible pavement response using LA and NLA was performed in this study. Tow structural analysis programs namely SAP90 and ANSYS5.3 were used for LA and NLA respectively. SAP90 is a FE structural analysis program [2]. It deals with linear elastic materials. In this study, surface deflections and stresses were obtained from the SAP90 solution phase. While, strains were computed from the equations relates stresses and strains for isotropic materials [3]. ANSYS5.3 is a finite element multipurpose program [3]. It deals with limit material properties for NLA. So, it allows different material properties in tension and compression.

ANALYSIS MODELS

The flexible pavement structure was assumed to have three layers (asphalt concrete, untreated base, and subgrade). The interface between any two consecutive layers was assumed to be perfectly bonded as recommended by the asphalt institute [4]. A Cartesian coordinate system was used in this analysis. The x and y axes are parallel to the longitudinal and transverse directions of the pavement respectively, while the z-axis represented the pavement depth. The positive direction of the x-axis is the traffic direction. The origin of the Cartesian coordinates is located exactly at the loading center of the contact area.

The properties required for each layer were the thickness (h), Poisson's ratio (ν), and modulus of elasticity (E) for linear analysis. In addition to these properties, tensile and compressive strengths (f_t & f_c) were required for non-linear analysis. The layer properties data for analysis model were, $E_1 = 1000$ MPa, $E_2 = 250$ MPa, and $E_3 = 50$ MPa. The Poisson's ratio were $\nu_1 = 0.35$, $\nu_2 = 0.30$, and $\nu_3 = 0.40$. The thicknesses of the layers were h_1 varied from 5 to 15 cm, $h_2 = 25$ cm, and $h_3 = 90$ cm such that the depth of the finite element model was taken $\geq$ four times the diameter of the wheel-pavement contact area (30 cm as mentioned later), so the stresses at this depth were very small.

Where :

E_1, E_2 and E_3	Moduli of asphalt concrete, untreated base and subgrade, respectively.
ν_1,ν_2 and ν_3	Poisson's ratios of asphalt concrete, untreated base and subgrade, respectively.
h_1, h_2 and h_3	Thicknesses of asphalt concrete, untreated base and subgrade, respectively.

Other data required for NLA are presented in Table 1. In this table, by assuming $f_t = 0.0001$ for both untreated base and subgrade layers, the program (ANSYS5.3) did not yield tensile stresses in these layers which have no tensile properties.

Table 1. Non-linear material properties

Layer	Compressive strength f_c (kg/cm^2)	Tensile strength f_t (kg/cm^2)
Asphalt concrete	60 *	3.19 **
Untreated base	15	0.0001
Subgrade	5	0.0001

1 kg/cm^2 = 14.221 psi.
* This value was obtained from reference [5].
** This value was obtained from reference [6].

A set of boundary conditions was defined for the model to provide stability to the structural system. The analysis model was established with a fixed boundary at the bottom and roller supports on sides, this conforms with the assumptions of W. Uddin et al.[7]. A single wheel load of 40 kN was applied over a circular contact area of 30 cm diameter. In addition to VWL, HF was applied in the longitudinal direction which represented tractive or braking effort. The value of this force varied depending on the coefficient of road adhesion (μ). The peak value of μ ranges from 0.8 to 0.9 for dry asphalt pavements and from 0.5 to 0.7 for wet asphalt pavements. But the maximum allowable peak value of the coefficient of road adhesion (μ_p) according to AASHTO is about 42 % in longitudinal direction [8], thus, a value of 0.4 was used as the coefficient of road adhesion in this study. This value results in longitudinal force (LONGF) of 16 kN. Another HF may act in lateral direction due to camber thrust, centripetal or any side force. The peak value of this lateral force equals to μ multiplied by VWL, but the allowable μ_p is about 17% in lateral direction [8]. Thus the coefficient of road adhesion in lateral direction was assumed equal to 0.2, this coefficient results in lateral force (LATF) of 8 kN. Table 2 illustrates the three load conditions applied to the flexible pavement system in this study.

Table 2. Load conditions

Load Condition	VWL only	0.2 VWL LONGF/LATF	0.4 VWL LONGF
Case 1	■		
Case 2	■	■	
Case 3	■		■

ANALYSIS OF COMPUTED PAVEMENT RESPONSE

Using the FE computer programs SAP90 and ANSYS5.3, sensitivity analysis was carried out to illustrate the effect of analysis type on asphalt pavement response.

This effect was studied for various AC layer thickness h_1. The sensitivity analysis was focused on the effect of the analysis type on the maximum surface deflection, the maximum compressive strain (ε_c) at the top of subgrade, and the maximum tensile strain (ε_t) at the bottom of the AC layer which are the most commonly used criteria for flexible pavement design. In addition to the mentioned comparison items, the maximum tensile stress in AC layer and the vertical stress distribution along the pavement depth were used to compare between LA and NLA.

Surface Deflections

Fig. 1 and Fig. 2 are samples of the surface deflection profiles for the studied cases using SAP90 for LA, and the corresponding cases using ANSYS5.3 for NLA. In view of these figures, a similar trend of surface deflection distribution was observed under various wheel loads. As anticipated, the maximum surface deflection occurred under the loading center and decreased gradually away from this center. For LA, there was no observed effect of the HF over the investigated range of its value on the maximum surface deflection. However, different surface deflection distributions were obtained due to these forces. For NLA, when applying HF in addition to VWL to the pavement system, the maximum surface deflection slightly increased, This increase was insignificant and can be neglected. A comparison of maximum surface deflection obtained from LA and NLA is presented in Table 3. The differences between LA and NLA are also given in this table. In view of Table 3, NLA yield lower surface deflection than LA. As h_1 increased, the difference between LA and NLA decreased, this confirms the findings of Chen et al. (1996), [1]. The thickness h_1 has a significant effect on the maximum surface deflection. This effect increased for NLA over that for LA.

Maximum Vertical Compressive Strains at the Top of the Subgrade Layer

Fig. 3 and Fig. 4 are examples for the effect of analysis type on the distribution of vertical strain at the top of the subgrade layer (ε_c). These figures show that, a similar behavior was noticed where the maximum value of ε_c occurred under the loading center and decreased gradually away from this center. Table 4 presents the maximum vertical compressive strains at the top of the subgrade layer for the studied cases for both LA and NLA. The differences between LA and NLA are also given in this table. NLA yield lower and more realistic vertical compressive strains at the top of the subgrade layer when compared with results obtained by Yue et al. [9]. Therefore, LA is more conservative regarding to rutting life of flexible pavements. The difference between LA and NLA decreased as h_1 increased, this confirms the findings of Chen et al. (1996), [1]. Table 4 shows also the advantage of using thicker AC layer to reduce ε_c and so resist permanent deformations.

Table 3. Maximum surface deflection (mm)

h1(cm)	Analysis Type	Load condition		
		VWL only	VWL + 0.2 VWL LONGF/LATF	VWL + 0.4 VWL LONGF
5	LA	1.1979	1.1979	1.1979
	NLA	0.7902	0.7931	0.7942
	difference (%)	34.03	33.79	33.70
10	LA	0.9928	0.9928	0.9928
	NLA	0.6086	0.6170	0.6115
	difference (%)	38.70	37.85	38.41
15	LA	0.8370	0.8370	0.8370
	NLA	0.4953	0.4959	0.4964
	difference (%)	40.82	40.75	40.69

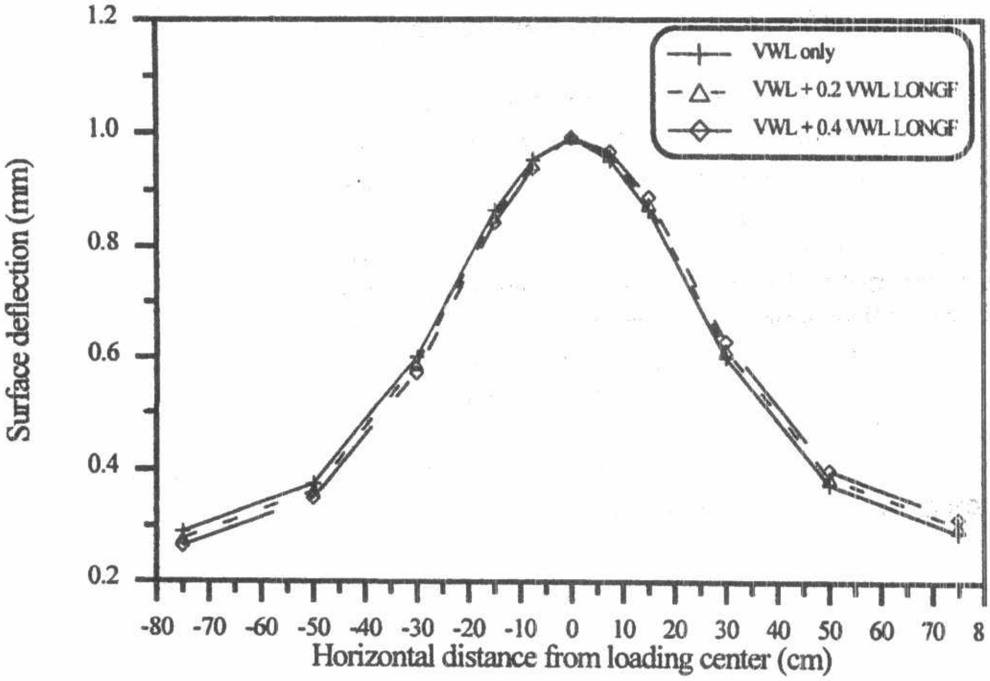

Fig. 1. Surface deflection distribution for h_1 = 10 cm, (LA).

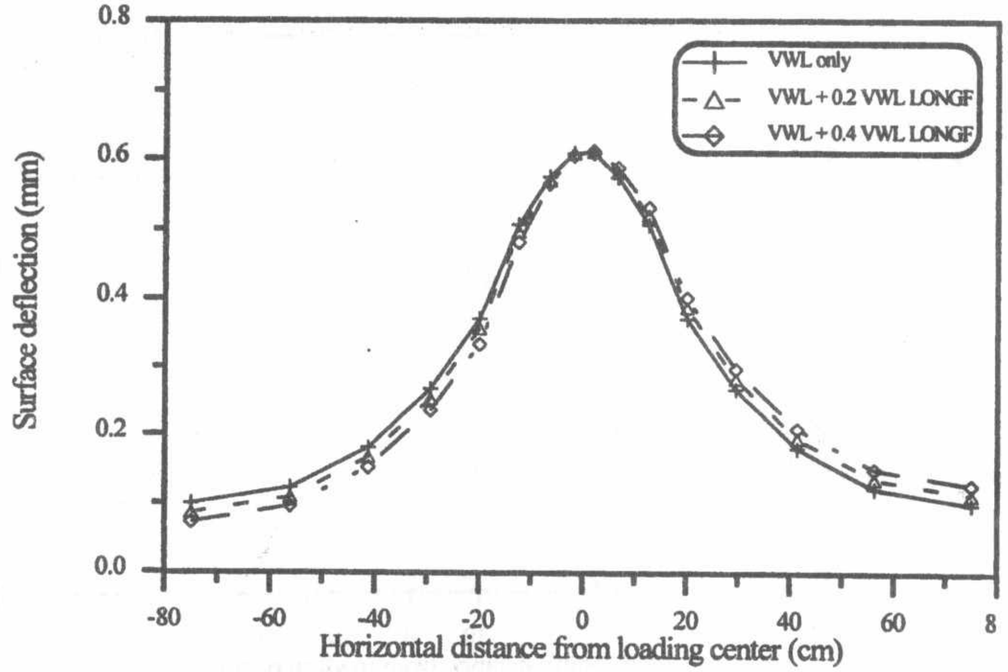

Fig. 2. Surface deflection distribution for h_1 = 10 cm, (NLA).

Table 4. Maximum vertical strain at the top of the subgrade layer (10^{-4})

h1(cm)	Analysis Type	Load condition		
		VWL only	VWL + 0.2 VWL LONGF/LATF	VWL + 0.4 VWL LONGF
5	LA	62.74	62.74	62.74
	NLA	10.72	10.46	10.81
	difference (%)	82.91	83.33	82.77
10	LA	45.40	45.40	45.40
	NLA	8.60	8.33	8.31
	difference (%)	81.06	81.65	81.70
15	LA	32.73	32.73	32.73
	NLA	6.79	6.28	6.08
	difference (%)	79.25	80.81	81.42

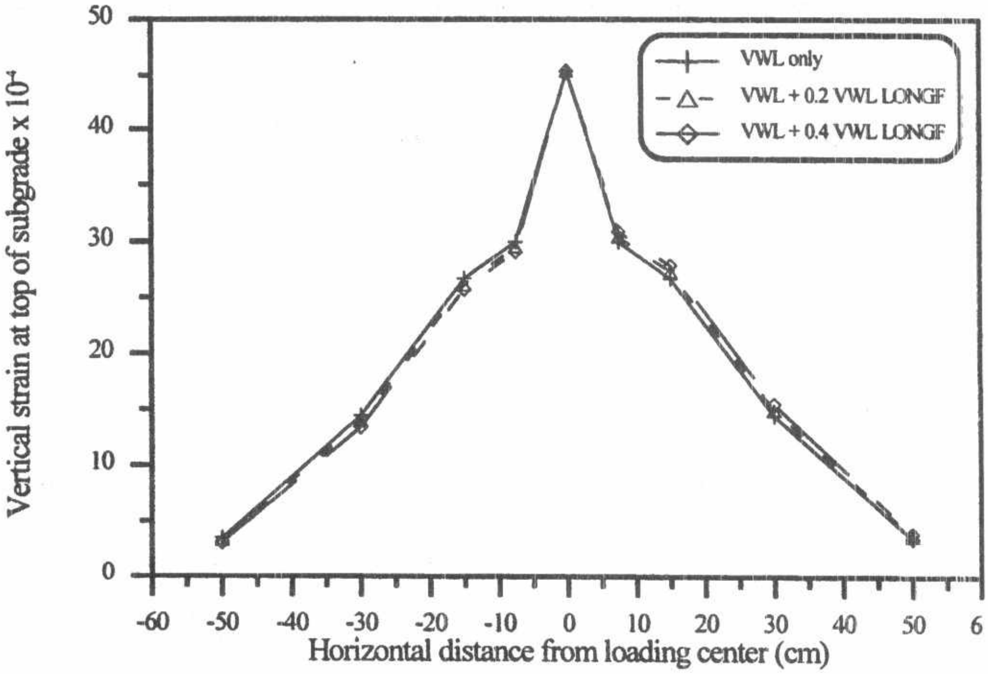

Fig. 3. Vertical compressive strain distribution at top of subgrade for h_1 = 10 cm, (LA).

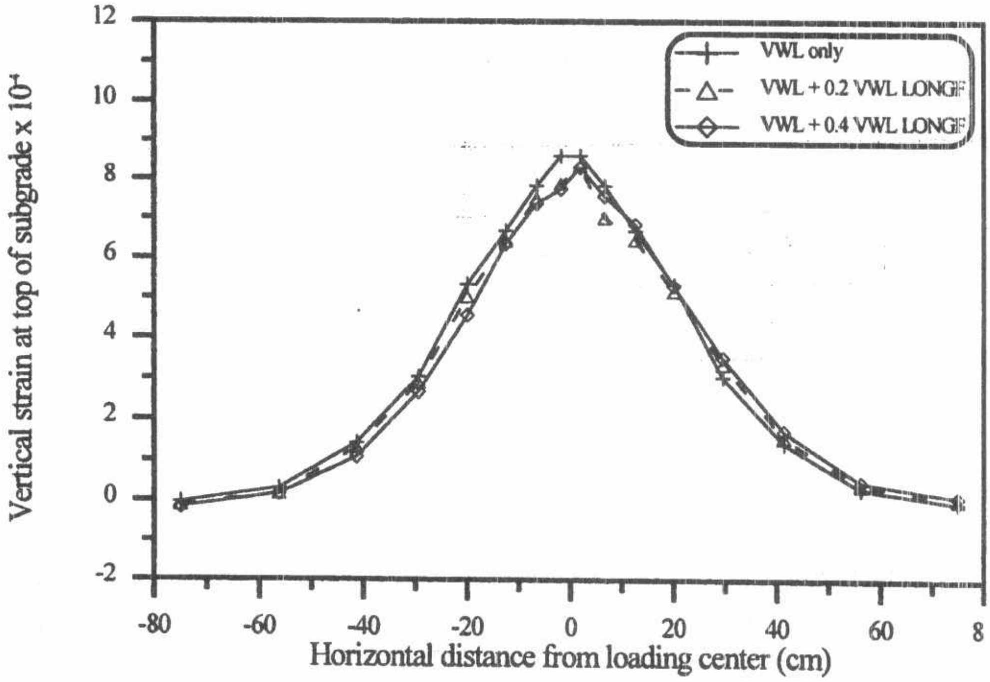

Fig. 4. Vertical compressive strain distribution at top of subgrade for h_1 = 10 cm, (NLA).

Maximum Tensile Strain at the Bottom of the AC Layer

The effect of analysis type on the maximum tensile strain at the bottom of the AC layer (ε_t), is presented in Table 5. Also the differences between NLA and LA are given in this table. It was found that, NLA gave higher tensile strains than LA. That was due to lesser tensile strength of the AC layer compared with its compressive strength and no tensile strength of untreated base and subgrade. These facts were used in NLA. Then NLA is more conservative regarding to fatigue life of flexible pavements. Fig. 5 and Fig.6 are samples of the studied cases and illustrate the distributions of horizontal strain at the bottom of the AC layer (ε_t) for different h_1 values for LA and NLA, respectively. These figures show that NLA result in more reasonable ε_t distribution, since it yield higher ε_t (over those when applying VWL only) behind the tire-pavement contact area where tension was expected. It yield lower ε_t where compression was expected due to the presence of HF. This anticipated behavior was not satisfied when using LA.

Table 5. Maximum horizontal tensile strain at the bottom of the AC layer (10^{-4})

h1(cm)	Analysis Type	Load condition		
		VWL only	VWL + 0.2 VWL LONGF/LATF	VWL + 0.4 VWL LONGF
5	NLA	2.816	3.288	16.598
	LA	2.196	3.029	3.867
	difference (%)	22.02	7.88	76.70
10	NLA	4.488	6.666	7.164
	LA	3.070	3.118	3.306
	difference (%)	31.60	53.23	53.85
15	NLA	8.613	8.964	10.006
	LA	3.612	3.612	3.612
	difference (%)	58.06	59.71	63.90

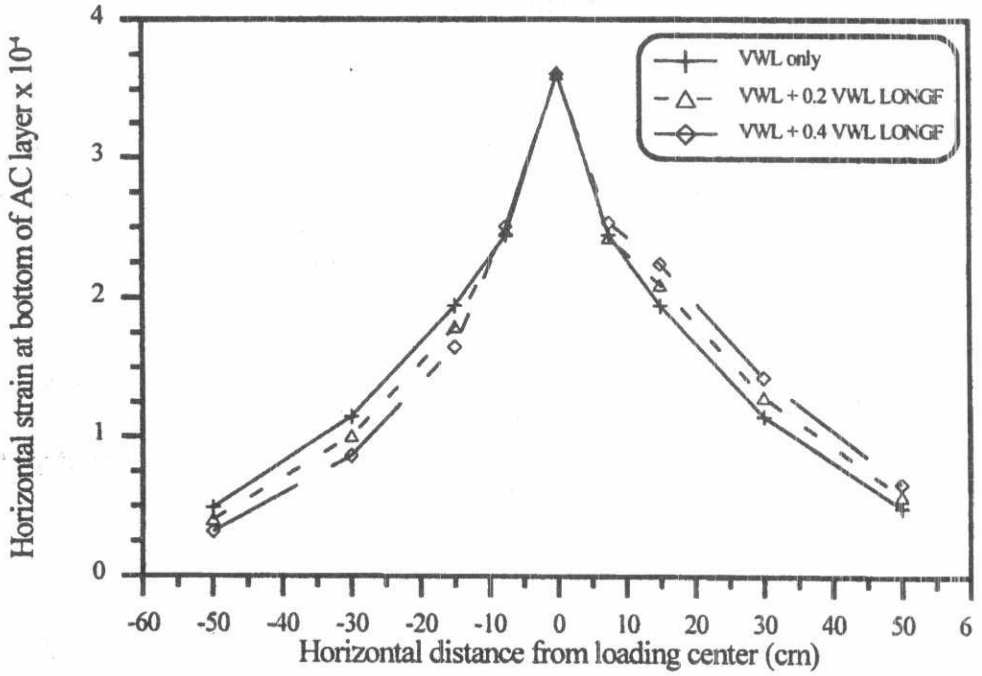

Fig. 5. Horizontal tensile strain distribution at bottom of AC layer for h_1 = 15 cm, (LA).

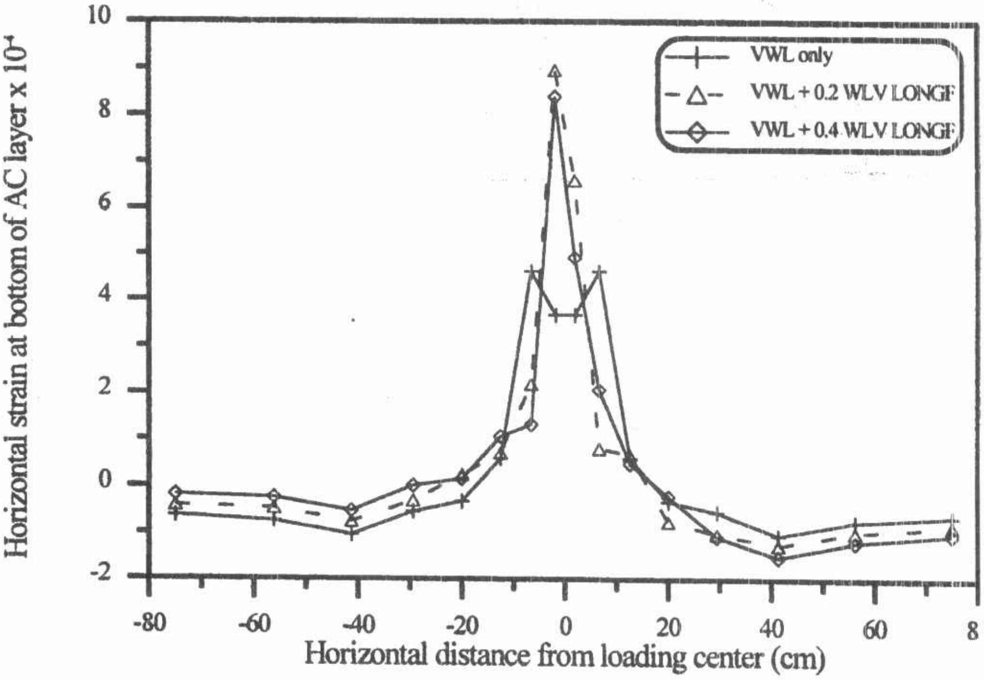

Fig. 6. Horizontal tensile strain distribution at bottom of AC layer for h_1 = 15 cm, (NLA).

Shoving in Asphalt Concrete Layer

If the tensile stresses in AC layer exceed its tensile strength, tearing takes place. Then it leads to shoving occurrence in flexible pavements. Knowing Marshall stability, tensile strength of AC can be calculated as discused in the indirect tensile test on AC samples. Marshall stability can be related to the AC modulus E_1 by the suggested AASHO layer coefficient nomographs [6]. Thus the estimated tensile strength for asphalt concrete was 44.56 psi. Table 6 presents the maximum tensile stress ($\sigma_{t\,max}$) in the AC layer for the studied cases of flexible pavement system subjected to different load conditions for AC layer thickness h_1 of 5, 10, and 15 cm. This table show that, for h_1 = 5 cm, $\sigma_{t\,max}$ obtained from NLA confirms those obtained from LA, specially when applying LATF = 0.2 VWL and LONGF = 0.4 VWL in addition to VWL to the pavement system. For h_1 = 15 cm, LA fall to properly describe the actual tensile stress in AC layer. It yield tensile stress in AC layer higher than its estimated tensile strength even under the application of VWL only. This appears to be unrealistic behavior of flexible pavements. It was believed that NLA yield more acceptable and realistic results than LA. For most cases, LA result in $\sigma_{t\,max}$ in AC layer higher than those obtained using NLA. Thus, LA is more conservative with regard to shoving.

Table 6. maximum tensile stress in the AC layer (psi)

h1(cm)	Analysis Type	Load condition		
		VWL only	VWL + 0.2 VWL LONGF/LATF	VWL + 0.4 VWL LONGF
5	LA	17.706	29.913	42.191
	NLA	30.34	30.37	43.45
	difference (%)	-71.35	-1.53	-2.98
10	LA	36.507	36.507	37.104
	NLA	33.48	24.40	30.12
	difference (%)	8.29	33.16	18.82
15	LA	54.981	54.981	54.981
	NLA	26.17	26.95	33.36
	difference (%)	52.40	50.98	39.32

Vertical Stress Distribution

Fig. 7 is an example to illustrate the vertical stress distribution beneath the loading center along the pavement depth for h_1 = 10 cm, for both LA and NLA. This figure shows that, LA fall to satisfy the boundary condition at the pavement surface. It yield vertical stress at pavement surface ranged from 273 to 303 kPa for different h_1, while the applied contact pressure was 552 kPa. NLA satisfied the surface boundary condition, it yield vertical stress ranged from 685 to 740 kPa depending on h_1 and load condition. The imposed contact pressure at the loading center was 696 kPa. Therefore, the results obtained from NLA were more reliable, and more acceptable than those obtained from LA.

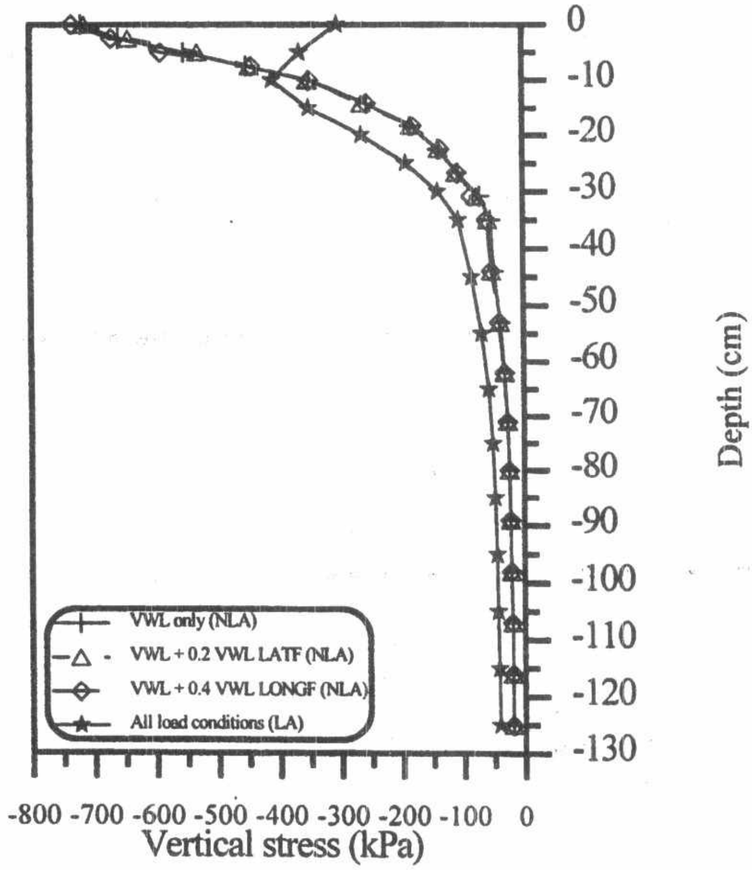

Fig. 7. Vertical stress beneath the loading center vs. pavement depth, for h_1 = 10 cm.

CONCLUSIONS AND RECOMMENDATIONS

Based on the work of this study it is found that, non-linear analysis is more realistic for flexible pavement analysis than linear analysis because of:

a) Non-linear analysis satisfies the surface boundary condition (the induced stress at surface corresponds to the imposed contact pressure between tire and pavement surface).

b) The vertical stress distribution along the pavement depth under loading center is more realistic, where the maximum vertical stress occurs at the pavement surface and decreases gradually with increasing the pavement depth.
c) Non-linear analysis gives more acceptable results when studying shoving. it yields tensile stresses in AC layer less than its tensile strength. The linear analysis yields tensile stresses in AC layer higher than its estimated tensile strength in many cases even under the application of VWL only to the flexible pavement system.
d) The distribution of horizontal tensile strain using non-linear analysis at the bottom of the asphalt concrete layer confirms the expected one.

Further studies using non-linear analysis model should be conducted to develop new design curves for flexible pavements. Finally, it is recommended to identify the effect of analysis type on flexible pavement response in airports field.

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