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Damaging Effect of Armoured Vehicles with Rubber Tires on Flexible Pavement

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Abstract

Presented in this paper is a new study of the damaging effect of military armoured vehicles with rubber tires on flexible pavements. Two types of military armoured vehicles with rubber tires were studied, namely LAV-AT four-axle and LAV-300 triple-axle. A measure of the damaging effect of military armoured vehicles with rubber tires loads was achieved by correlating their equivalent loads with the AASHTO equivalency factors. The equivalent load was developed on the basis of mechanistic - empirical approach. It was found that the damaging effect of the studied military armoured vehicles with rubber tires loads is 0. 0.200 to 4.736 times the damaging effect of the standard 18 kips (80 kN) axle load depending on the thickness of asphalt layer.

Keywords: military armoured vehicles, four-axle, triple-axle AASHTO equivalency factors, flexible pavements, and damaging effect.

التأثير التخريبي لأحمال ألعجلات المدرعة ذات الإطارات المطاطية على التبليط ألإسفلتي

الخلاصة

دراسة جديدة للتأثير التخريبي لأحمال ألعجلات المدرعة ذات الإطارات المطاطية رباعية وثلاثية المحاور على التبليط الإسفلتي من خلال أبجاد معاملات آشتو المكافئة لها ولأول مـــرة وباستخدام طريقة الحل الميكانيكي – التجريبي. لقد وجد إن تأثير الأحمال التخريبـــي لأحمـــال ألعجلات المدرعة ذات الإطارات المطاطية التي تمت دراستها يتراوح من 0.200 إلى 4.736 مرة تأثير حمل آشتو القياسي حسب سمك طبقة الإسفلت.

1. Introduction

Determining the pavement life under given structural, environmental, and traffic conditions is considered the main objective in the pavement design and analysis. The American Association of State Highway and Transportation Officials (AASHTO) Design Guide estimates pavement life in terms of the number of equivalent single axle loads (ESAL's). Its design equation was established through empirical analysis primarily based on the AASHO Road Test in Ottawa, Illinois conducted during the late 1950s. The deterioration of a roadway is accelerated over time by the repeated application of loads generated by heavy vehicles. Consequently projected maintenance and preservation costs increase. Pavement deterioration is further intensified by an incentive for overweight trucks

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due to economic benefits of an increased payload (Paxson and Glickert, 1982).

The effect of the traffic using these roads should be focused upon carefully from the standpoint of pavement structural design. Yoder and Witczak (1975) reported that this effect includes among other considerations, the expected vehicle type and the corresponding number of repetitions of each type during the design life of the pavement. The effect of various types of vehicles (axles) on the structural design of road pavement is considered by means of the approach of axle load equivalency factor. In this approach, a standard axle load is usually used as a reference and the damaging effect of other axle loads (corresponding to various types of axles) is expressed in terms of number of repetitions of the standard axle.

The AASHTO standard axle is the 18 kips (80 kN) single axle with dual tires on each side (Yoder and Witczak, 1975). Thus, the AASHTO equivalency factor defines the number of repetitions of the 18 kips (80 kN) standard axle load which causes the same damage on pavement as caused by one pass of the axle in question moving on the same pavement under the same conditions. The AASHTO equivalency factor depends on the axle type (single, tandem, or triple), axle load magnitude, structural number (SN), and the terminal level of serviceability (pt).

The effect of structural number (SN) and the terminal level of serviceability (pt) are rather small; however, the effect of axle type and load magnitude is pronounced (Razouki and Hussain, 1985). There are types of vehicle loads that not included in the AASHTO road test such as the military armoured vehicles that move on paved roads occasionally during peace times and frequently during war times. The effect of the military armoured vehicle loads on flexible pavements is not known, and not mentioned in the literature up to the capacity of the author's knowledge. Therefore, this research was carried out to find the AASHTO equivalency factors and the damaging effect of military armoured vehicles that move frequently on our roads network (even on small local paved streets) on daily bases for more than six years up to now. There are two main approaches used by researchers to determine the equivalency factors, the experimental and the mechanistic (theoretical) approach. A combination of two approaches was also used by Wang and Anderson (1979).

In the mechanistic approach, some researchers adopted the fatigue concept analysis for determining the destructive effect (Havens et al., 1979), while others adopted the equivalent single wheel load procedure for such purposes (Kamaludeen, 1987). The mechanistic empirical approach is used in this research depending on fatigue concept. Following Yoder and Witczak (1975), AASHTO design method recommended the use of 18 kips (80 kN) standard axle with dual tires on each side, thus, the AASHTO equivalency factor $\mathbf{F_j}$ is:

$$F_j = \left(\frac{\varepsilon_j}{\quad}\right)^c \qquad \text{........ (1)}$$

ε_s

where, ε_j , ε_s = the maximum principal tensile strain for the jth axle and the 18 kips standard single axle respectively and c represent regression constant. Yoder and Witczak (1975) reported that both laboratory tests and field studies have indicated that the constant c ranges between 3 and 6 with common values of 4 to 5.

Van Til et al**.** (1972) and AASHTO (1986) recommended two fatigue criteria for the determination of AASHTO equivalency factors namely, the tensile strain at the bottom fiber of asphalt concrete and the vertical strain on sub-grade surface. AASHTO (1986) reported a summary of calculations for tensile strain at the bottom fiber of asphalt concrete (as fatigue criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements.

Also, AASHTO (1986) reported a summary of calculations for vertical compressive strain on sub-grade surface (as rutting criterion) due to the application of 18 kips standard axle load on flexible pavement structures similar to that of original AASHTO road test pavements. The AASHTO (1986) calculated strains are function of the structural number (SN), the dynamic modulus of asphalt concrete, the resilient modulus of the base materials, the resilient modulus of roadbed soil, and the thickness of pavement layers.

These reported AASHTO (1986) strains which represent (ε_s) in equation (1) above in addition to Van Til et al. (1972) & Huang (1993) reported experimental values for the constant c in equation (1) above for different pavement structures. Huang (1993) reported that in fatigue analysis, the horizontal minor principal strain is used instead of the overall minor principal strain. This strain is called minor because tensile strain is considered negative. Horizontal principal tensile strain is used because it is the strain that causes the crack to initiate at the bottom of asphalt layer. The horizontal principal tensile strain is determined from:

$$\varepsilon_r = \frac{\varepsilon_x + \varepsilon_y}{2} - \sqrt{\left(\frac{\varepsilon_x - \varepsilon_y}{2}\right)^2 + (\gamma_{xy})^2} \quad \ldots\ldots(2)$$

where, ε_r = the horizontal principal tensile strain at the bottom of asphalt layer, ε_x = the strain in the x direction, ε_y = the strain in the y direction, γ_{xy} = the shear strain on the plane x in the y direction. Therefore, (ε_r) of equation (2) represents (ε_j) of equation (1) and will be used in fatigue analysis in this research. These two criteria were used in this research to determine the AASHTO equivalency factors of military armoured vehicles. The tensile strains at the bottom fiber of asphalt concrete and vertical compressive strains on sub-grade surface of similar pavement structures to that of AASHTO road test as reported by AASHTO (1986) were calculated under military armoured vehicles in this research. KENLAYER linear elastic computer program (Huang, 1993) was used to calculate the required strains, and stresses in this research at 400 points each time in three dimensions at different locations within AASHTO reported pavement structures under military armoured vehicles.

2. Characteristics of military armoured vehicles with rubber tires

The characteristics of military armoured vehicles which required in this research are their three dimensions (height, length, and width) in addition to the weight. These features were obtained from the brochure of their manufacturing company (General Dynamics Land Systems, 2010) and the website (The Federation of American Scientists, 2010). Two types of military armoured vehicles with rubber tiers were taken for the purpose of this study as follows (see Figure (1) and Figure (2)):

1. LAV-AT four-axle eight-wheel military armoured vehicle was chosen to represent the family of four-axle military armoured vehicles with rubber tiers because it is widely used and can be converted to any other type and purpose.
2. LAV-300 triple-axle six-wheel military armoured vehicle was chosen to represent the family of triple-axle military armoured vehicles with rubber tiers because it is widely used and can be converted to any other type and purpose.

3. Analysis Methodology

3.1 AASHTO equivalency factors of military armoured vehicles

Three-layer pavement structure was taken as mentioned in the introduction above to simulate AASHTO original road test pavements as shown in Figure (1) and Figure (2). Only one set of values for the modulus of asphalt layer (E_1 =1035.5 MPa), the base layer (E_2 =103.5 MPa), and the sub-grade modulus (E_3 =51.7 MPa) was taken from the original AASHTO road test because it is similar to the modulus values of local materials in practice] (Kamaludeen, (1987). AASHTO Poisson's ratios of 0.4 for asphalt layer, 0.35 for base layer, and 0.4 for sub-grade layer were taken for the purpose of this analysis. Two types of military armoured vehicles with rubber tires were studied, namely LAV-AT four-axle and LAV-300 triple-axle as shown in Table (1).

3.1.1 AASHTO equivalency factors of LAV-AT military armoured vehicle

LAV-AT four-axle eight-wheel multipurpose military armoured vehicle was used to represent the family of four-axle military armoured vehicles that is widely used world wide. Three-layer pavement structure was taken as mentioned in the introduction above to simulate AASHTO original road test as shown in Figure (1). The contact areas of the eight wheels were calculated using three values for tire pressure namely, 0.828, 0.69, and 0.552 MPa respectively to study the effect of tire pressure on the AASHTO equivalency factors of these military armoured vehicle loads. The total combat weight of 12.55 tons was distributed equally on the eight wheels because these vehicles have load distribution mechanism on equal bases. Figure (3), Figure (4), and Figure (5) were prepared to show the calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer respectively under LAV-AT military armoured vehicle. These strains were obtained for 400 calculating points for each one of these figures with a tire pressure of 0.828 MPa and using KENLAYER computer program

(Huang, 1993). Figure (6) was prepared to show the calculated vertical compressive strains on the surface of sub-grade layer of AASHTO pavement structure shown in Figure (1) under LAV-AT armoured vehicle with a tire pressure (contact pressure) of 0.828 MPa. These strains were obtained for 400 calculating points using KENLAYER computer program (Huang, 1993). It was found that the calculated tensile strains in the direction of x, y, and r at the bottom fiber of asphalt concrete layer are much more conservative than calculated vertical compressive strains on the surface of sub-grade layer under LAV-AT military armoured vehicle in comparison with their similar type of strains reported by AASHTO (1986), as shown in Figure (3) to Figure (6).

Therefore, the fatigue criterion governed and was used to calculate the AASHTO equivalency factors of LAV-AT military armoured vehicle. The maximum calculated horizontal principal tensile strains (ε_r) at the bottom fiber of asphalt concrete layer under LAV-AT military armoured vehicle for the AASHTO (1986) pavement structures are summarized in Table (2). The AASHTO (1986) reported maximum tensile strains (ε_t) at the bottom fiber of asphalt concrete layer for the AASHTO pavement structures under the standard 18 kips (80 kN) are shown also in Table (2). The values for the constant c of equation (4) for each of AASHTO (1986) pavement structure were obtained from the values of Asphalt Institute as mentioned by Huang (1993). The AASHTO equivalency factors of LAV-AT military armoured vehicle were calculated using equation (1) as shown in Table (2).

The maximum tensile strains in the direction of x and y at the bottom fiber of asphalt concrete layer and the vertical compressive strains on the surface of sub-grade layer under LAV-AT military armoured vehicle for the AASHTO (1986) pavement structures were recalculated using different tire pressure values of LAV-AT military armoured vehicle to study the effect on strain values as shown Table (3). These strains were calculated using only one AASHTO pavement structure shown in Figure (1) above. It was found that the tire pressure has very small effect on the value of strain and later on the value of AASHTO equivalency factors of LAV-AT military armoured vehicle loads. This can be attributed to the high load magnitude and the interlocking of the effects of eight loaded tires in three dimensions.

3.1.2 AASHTO equivalency factors of LAV-300 military armoured vehicle.

The same procedure mentioned in paragraph 3-1 above to determine the AASHTO equivalency factors of LAV-AT load as shown in Table (2) was repeated to determine the AASHTO equivalency factors of LAV-300 military armoured vehicle as shown in Table (4). The only exception that the dimensions and weight of LAV-300 military armoured vehicle were used instead of the dimensions and weight of LAV-AT. Table (4) was prepared following the same procedure in preparing Table (2) to show the AASHTO equivalency factors of LAV-300 load respectively. Also, the fatigue criterion governed and was used to calculate the AASHTO equivalency factors of LAV-300 military armoured vehicle load. The maximum calculated horizontal principal tensile strain (ε_r) at the bottom of asphalt layer under LAV-300 vehicle load for load layout shown in Figure (2) above for the AASHTO (1986) pavement structure are summarized in Table (4).

4. Discussion of results and Conclusions

It was found that the military armoured vehicles with rubber tires have a pronounced damaging effect on flexible pavements in terms of AASHTO equivalency factors as follows:

1- The AASHTO equivalency factors of LAV-AT military armoured vehicle load were found to be from 0.200 to 3.488 based on fatigue criterion. Increasing the thickness of the asphalt layer pavement decreases the AASHTO equivalency factors of LAV-AT military armoured vehicle load. This means that the structural damaging effect LAV-AT military armoured vehicle load on flexible pavements of secondary and local roads is higher than its damaging effect on the flexible pavement of major roads and highways. It was found that increasing the tire pressure has very small effect on the AASHTO equivalency factors of LAV-AT military armoured vehicle load from the theoretical point of view due to the high magnitude of LAV-AT military armoured vehicle load.

2- The AASHTO equivalency factors of LAV-300 military armoured vehicle load were found to be from 0.875 to 4.736 based on fatigue criterion. Increasing the thickness of the asphalt layer pavement decreases the AASHTO equivalency factors of CM31 military armoured vehicle load. This means that the structural damaging effect CM31 military armoured vehicle load on flexible pavements of secondary and local roads is higher than its damaging effect on the flexible pavement of major roads and highways.

5. Recommendations

Based on the results of this study, an economic evaluation for the cost of damage that had been caused by the frequent movement of military armoured vehicles with rubber tires on the whole national road network during the last six years is required. Also, another study is necessary to determine the damaging effect of military armoured vehicles with rubber tires on the national road network during summer seasons.

Notations

F_j AASHTO equivalency factor.
c regression constant.
E_1 the modulus of asphalt layer.
E_2 the modulus of the base layer.
E_3 the modulus of subgrade layer.
t_1 thickness of asphalt layer.
t_2 thickness of base layer.

Greek letters

ε_j the maximum principal tensile strain for the jth axle.
ε_s the maximum principal tensile strain for the 18 kips standard single axle.
ε_r the horizontal principal tensile strain at the bottom of asphalt layer.
ε_x the strain in the x direction.
ε_y the strain in the y direction.
γ_{xy} the shear strain on the plane x in the y direction.
ε_v compressive strain on the top of subgrade soil.

ε_t tensile strain at the bottom of asphalt layer.

μ_1 Poisson's ratio of asphalt layer.

μ_2 Poisson's ratio of the base layer

μ_3 Poisson's ratio of subgrade layer.

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Table (1) Features of the two studied military armoured vehicles.

Features	Type of military armoured vehicle	
	LAV-AT Four-axle	LAV-300 Triple-axle
Length (m)	6.40	6.40
Width (m)	2.49	2.54
Height (m)	2.69	1.98
Combat Weight (ton)	12.55	14.50

Table (2) AASHTO equivalency factors of LAV-AT military armoured vehicle using fatigue criterion and for load layout in Figure (1).

Modulus Layer 1 = 1035.5 MPa, μ_1 = 0.40						
Modulus Layer 2 = 103.5 MPa, μ_2 = 0.35						
Modulus Layer 3 = 51.724 MPa, μ_3 = 0.40						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Asphalt Tensile strain (ε_t)	SN	c	LAV-AT AASHTO Equivalency Factor
7.62	56.64	AASHTO(1)	0.0006212	4	4.48	3.488
7.62	56.64	Calculated(2)	0.0008210	4	4.48	3.488
10.16	47.50	AASHTO(1)	0.0005395	4	4.48	1.437
10.16	47.50	Calculated(2)	0.0005850	4	4.48	1.437
12.70	59.18	AASHTO(1)	0.0004561	5	4.48	0.752
12.70	59.18	Calculated(2)	0.0004280	5	4.48	0.752
15.24	50.04	AASHTO(1)	0.0003897	5	4.48	0.200
15.24	50.04	Calculated(2)	0.0002720	5	4.48	0.200
20.32	52.58	AASHTO(1)	0.0002854	6	4.48	0.217
20.32	52.58	Calculated(2)	0.0002030	6	4.48	0.217

(1) AASHTO (1986) maximum horizontal strain (ε_t) at the bottom fiber of asphalt layer under the standard 18 kips (80 kN) axle load for serviceability (Pt) of 2.0.
(2) Calculated maximum horizontal principal tensile strain (ε_r) at the bottom of asphalt layer under LAV-AT for load layout shown in Figure (1) above.

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Table (3) Effect of tire pressure of LAV-AT four-axle eight-wheel military armoured vehicles on strains(*).

Tire Pressure MPa	Max. Tensile Strain (ε_x)	Max. Tensile Strain (ε_y)	Max. Compressive Strain (ε_v)
0.828	0.0008210	0.0008210	0.0001840
0.690	0.0006570	0.0006570	0.0001800

(*): Maximum strains ε_x, ε_y, and ε_z were calculated for the pavement structure shown in Figure (3), (E_1=1035.5 MPa, E_2=103.5 MPa, E_3=51.7 MPa, t_1=7.6 cm, t_2=56.6 cm, μ_1=0.4, μ_2=0.35, and μ_3=0.4).

Table (4): AASHTO equivalency factors of LAV-300 triple-axle six-wheel military armoured vehicle using fatigue criterion and for load layout in Figure (2).

Modulus Layer 1 = 1035.5 MPa, μ_1 = 0.40						
Modulus Layer 2 = 103.5 MPa, μ_2 = 0.35						
Modulus Layer 3 = 51.724 MPa, μ_3 = 0.40						
Thickness Layer 1 cm	Thickness Layer 2 cm	Source of Data	Asphalt Tensile strain (ε_t)	SN	c	LAV-300 AASHTO Equivalency Factor
7.62	56.64	AASHTO(1)	0.0006212	4	4.48	4.736
7.62	56.64	Calculated(2)	0.0008790	4	4.48	4.736
10.16	47.50	AASHTO(1)	0.0005395	4	4.48	2.933
10.16	47.50	Calculated(2)	0.0006860	4	4.48	2.933
12.70	59.18	AASHTO(1)	0.0004561	5	4.48	2.043
12.70	59.18	Calculated(2)	0.0005350	5	4.48	2.043
15.24	50.04	AASHTO(1)	0.0003897	5	4.48	1.506
15.24	50.04	Calculated(2)	0.0004270	5	4.48	1.506
20.32	52.58	AASHTO(1)	0.0002854	6	4.48	0.875
20.32	52.58	Calculated(2)	0.0002770	6	4.48	0.875

(1) AASHTO (1986) maximum horizontal strain (ε_t) at the bottom fiber of asphalt layer under the standard 18 kips (80 kN) axle load for serviceability (Pt) of 2.0.

(2) Calculated maximum horizontal principal tensile strain (ε_r) at the bottom of asphalt layer under LAV-300 for load layout shown in Figure (2) above.

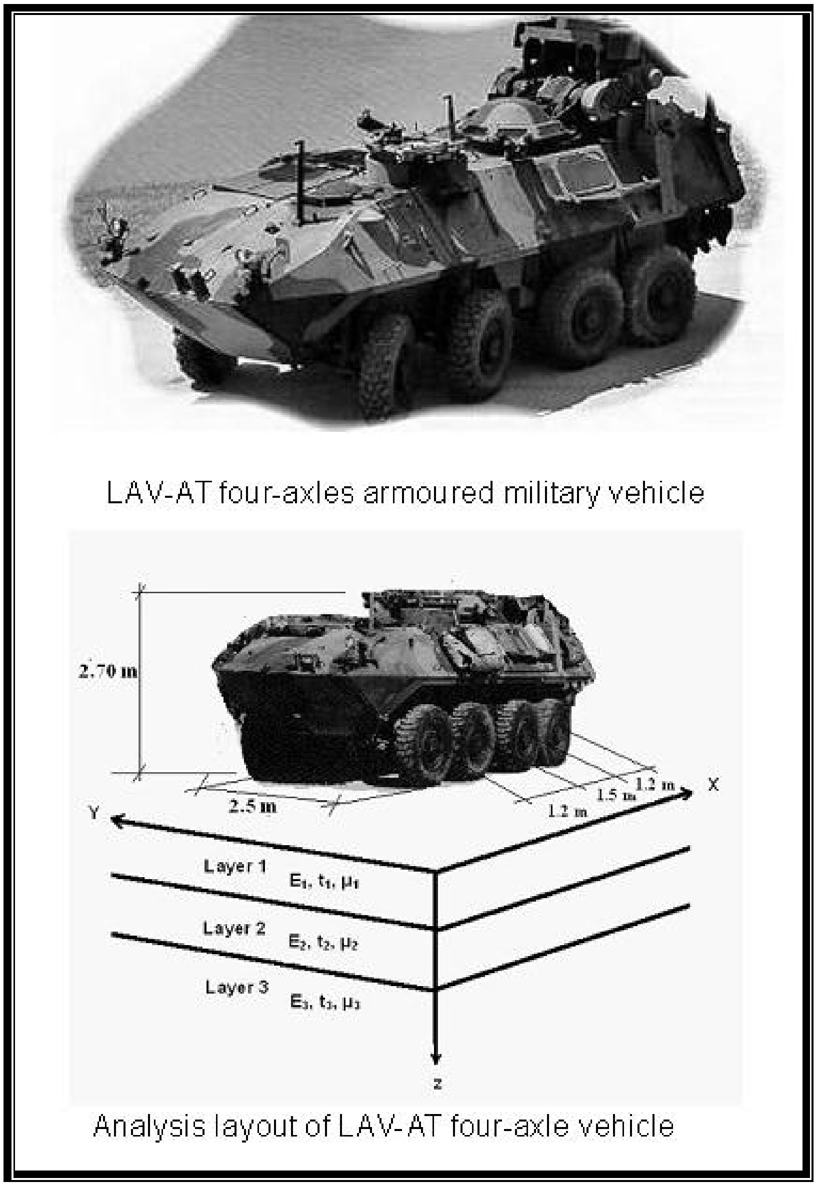
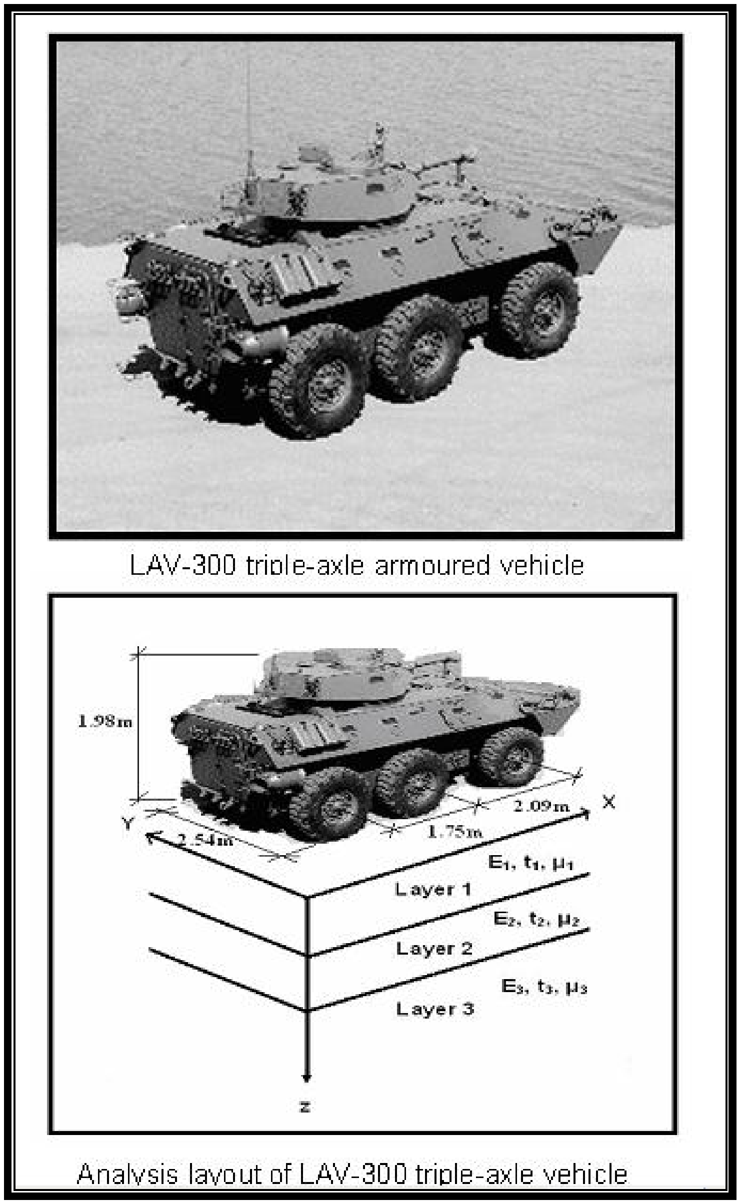


Figure (1) LAV-AT four-axle military armoured vehicle with rubber tiers used in the study.



LAV-300 triple-axle armoured vehicle

Analysis layout of LAV-300 triple-axle vehicle

Figure (2) LAV-300 triple-axle military armoured vehicle with rubber tiers used in the study.

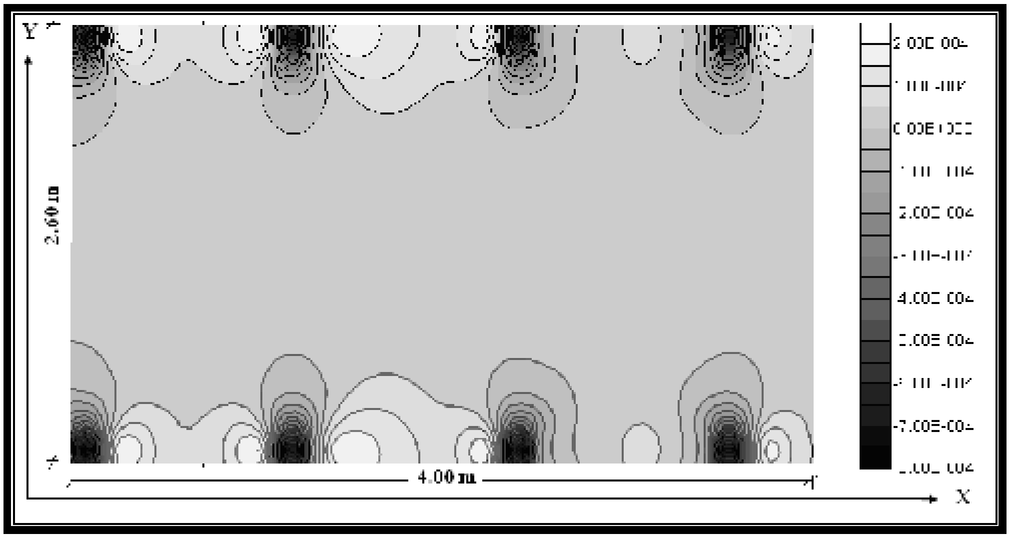


Figure (3) Tensile strain in the x direction (ε_x) at the bottom fiber of asphalt layer (t_1=7.6 cm and t_2=56.6 cm).

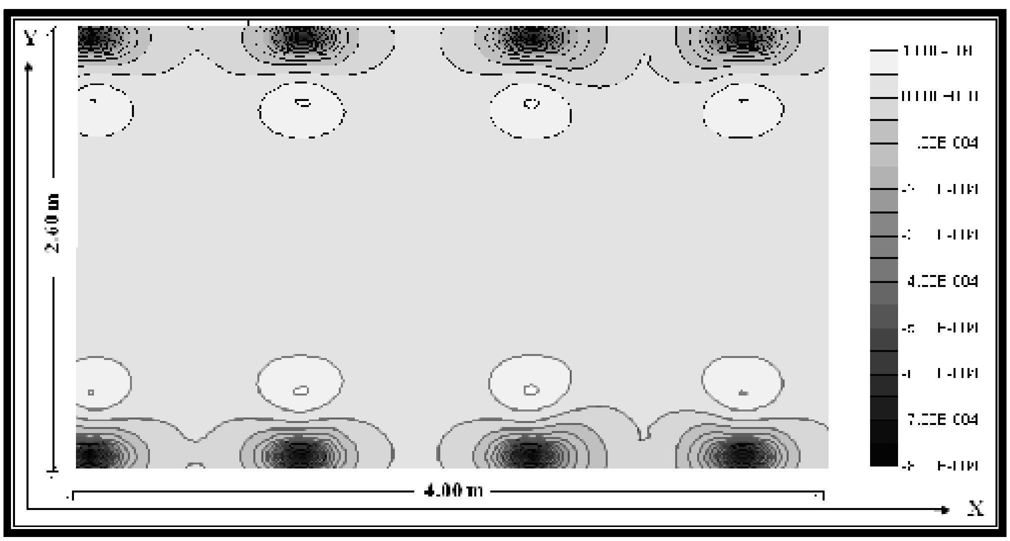


Figure (4) Tensile strain in the y direction (ε_y) at the bottom fiber of asphalt layer (t_1=7.6 cm and t_2=56.6 cm).

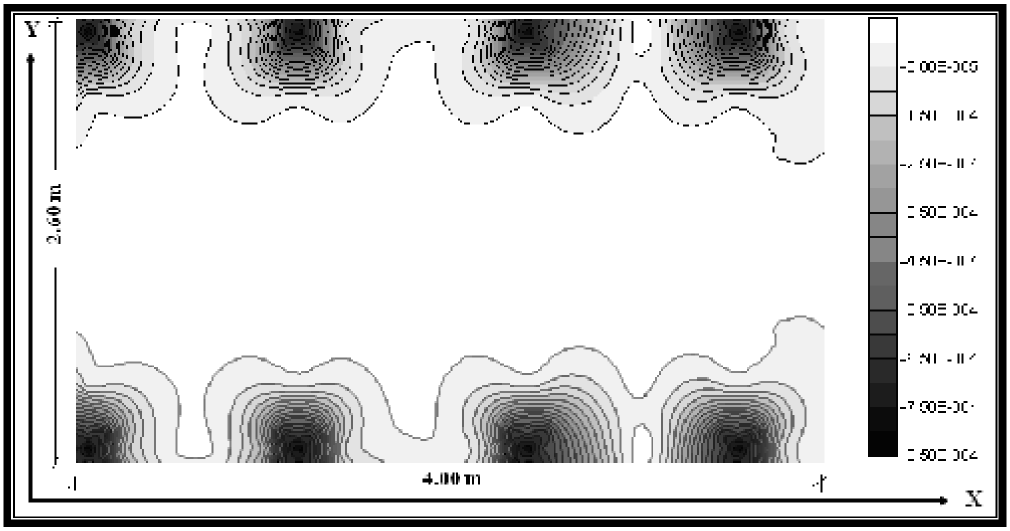


Figure (5) Horizontal principal tensile strain at the bottom of asphalt layer (ε_r) (t_1=7.6 cm and t_2=56.6 cm).

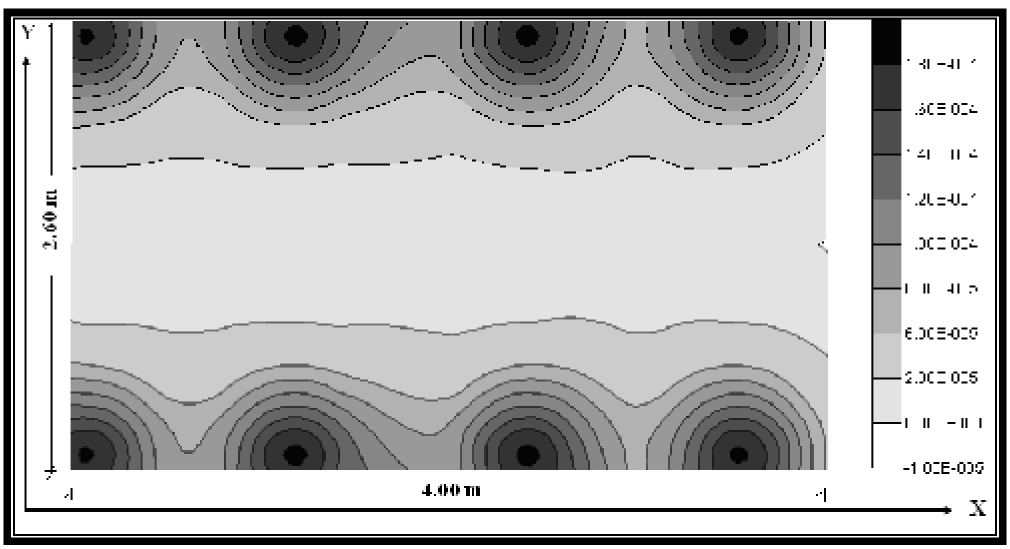


Figure (6) Vertical strain in the z direction (ε_z) on the surface of sub-grade layer (t_1=7.6 cm and t_2=56.6 cm).