Numerical modelling of geosynthetic-reinforced unpaved roads using FLAC 2D

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ABSTRACT: Assessment of pavement performance is typically carried out by field trails, large-scale laboratory experiments, and numerical modelling. In this study, a numerical model of unpaved road constructed with competent and marginal aggregate bases over soft subgrade with and without reinforcement (planar) under plain-strain condition was developed using two-dimensional explicit finite difference program - Fast Lagrangian Analysis of Continua (FLAC2D). Base layer and subgrade soil were modelled by continuum zones following Mohr-Coulomb failure criterion and the reinforcement was modelled as structural element cable. The mesh size and the maximum unbalanced force ratio were selected based on convergence and computational time to obtain the solution. Large-strain mode was activated in the study so that the coordinates of the grid points were updated at the end of every cycle. A series of numerical simulations were conducted in displacement-controlled mode for different properties of base layer and subgrade soil to assess the effectiveness of the reinforcement.
The improvement in reinforcing base layer was presented in terms of load improvement factor, the normal stress transferred at the subgrade layer, and settlement at the surface. In addition, the axial force and axial strain mobilized in the reinforcement was also presented. The effectiveness of the reinforcement was found to be significant for settlement ratios beyond 4%.

Keywords: Unpaved Road, Geosynthetic Reinforcement, Numerical Modelling, FLAC2D, Load Improvement Factor

1 INTRODUCTION

Reinforcing the flexible pavements is widely adopted to improve the performance or to reduce the consumption of aggregate for a given service life. The performance of flexible pavement can be studied by means of full-scale field trails, accelerated pavement testing, large-scale laboratory experiments and numerical modelling. Full-scale field trails can provide very reliable and actual performance information, however an agency has to invest considerable amount of funds, effort and time to execute them. Large-scale laboratory experiments can be used to study the performance behavior of the flexible pavements. It is very important to consider scale effects and boundary conditions to obtain and report reliable results from large-scale experiments and they also need considerable amount of effort, time and funds.

It is well known that unbound materials in flexible pavement systems exhibit nonlinear stress-strain response. However, current pavement design procedures are based on linear elastic analysis for determination of the flexible pavement response. Therefore, it is instructive to study the differences between the results from linear elastic analysis and those from nonlinear analysis (ARA Inc. 2004).

Many researchers studied the effect of geosynthetic reinforcement on performance of paved and unpaved roads over soft subgrade using large-scale laboratory tests and numerical modelling methods,, while countable number of field trails prove the benefit of geogrids, however the performance of reinforced flexible pavements under different conditions such as with stiff reinforcement, and marginal aggregate base course is still not clear.

Finite difference method is one of the many techniques available to determine stresses, strains and deformations in flexible pavement systems. In the present work, a comprehensive study was undertaken to assess the performance of reinforced flexible pavements under static loading with different reinforcements and base course materials using two-dimensional explicit finite difference program - Fast Lagrangian Analysis of Continua, FLAC2D software.

2 PAVEMENT ENGINEERING DECISION TOOLS

The tools available to the engineers to make decisions on pavements are engineering judgment, computer simulations, laboratory testing, field testing, accelerated pavement testing, construction and performance study of pavements relative to cost and associated knowledge (Hugo et al. 1991). The agency's ability to finance a particular combination of tools decides the selection of range and types of decision tools to yield the knowledge to design, construct, and manage highways. For optimal results, a range of tools should be selected encompassing all the tools to the left of the affordable budget cut off line. Engineering judgment forms an important part of any selection and is supplemented by the other methods to various degrees. To increase the dependability of a pavement system, however, more reliable methods must be used to predict the likelihood of distress occurrences. After the selection of distress criteria for pavements in a specific area, a plan must be developed and equipment acquired to obtain the input information, such as moduli, that relate the distress criteria to pavement performance. Figure 1 indicates that computer simulation is an inexpensive evaluation method with low to high range of knowledge about pavement performance; however, obtaining accurate input through testing and then deriving or improving the models for greater reliability depends on model calibration which are relatively expensive.

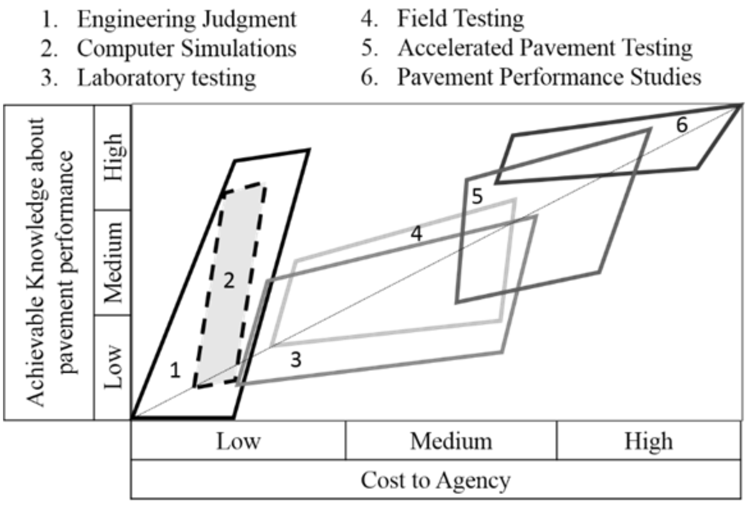


Figure 1 Financial investment by agency and associated knowledge about pavement performance (Adopted from Hugo et al. 1991)

Many techniques are available for determining the stresses, strains, and deformations in flexible pavement systems (ARA Inc. 2004). These can be classified as follows:

- Analytical
- Multilayer Elastic Theory
- Finite Difference Methods
- Finite Element Methods
- Boundary Element Methods
- Hybrid Methods

In a study by Duncan et al. 1968, they concluded that the axisymmetric finite element analyses may be applied to pavement problems and also indicate that it is feasible to approximate nonlinear material properties in the analyses of the pavement structures. While Giroud & Han 2004a state that the plane-strain two-dimensional case is representative of the case of a channelized traffic because the deformations associated with ruts of great length obviously create plane-strain conditions. In the present study plane-strain condition is assumed for the model of unpaved pavement system.

After analyzing the FLAC2D simulations of the pavement in both the cases of large strain and small strain, Benmebarek et al. 2013 concluded that the large-strain simulations show more improvement in the bearing capacity and simulate better the actual behavior. Hence, in the present study all the simulations are analyzed in large-strain mode.

3 MESH GEOMETRY AND BOUNDARIES

3.1 *Pavement model*

Model size used by Duncan et al. (1968) was 1.778 m (≈11B) in x-direction and 2.794 m (≈18B) in y-direction and loaded over three layered system for a distance of 152 mm (B) along x-direction from center line with a pressure of 689 kPa. Erickson & Drescher (2001) employed FLAC2D to model the reinforced flexible pavement, they used 1960 elements and graded square mesh of 2.0 m in size (≈13B). The appendix RR of the document by NCHRP Project 1-37A research team states that the vertical side boundaries for the mesh should be no closer than 10 to 12B, the horizontal bottom boundary at the base of the subgrade should be no closer than 50B ARA Inc. (2004). Benmebarek et al. (2013) used a mesh of size 3.18 m (20B) in x-direction and a depth of 2.752 m (17B) in y-direction with standard fixities and loading through 159 mm (B=a/2) from central axis. George and Saride (2014) used the vertical boundaries at 2.032 m in x-direction (≈13B) from the center of the load area, and the bottom boundary was at 2.027 m in y-direction (≈13B) and loaded through a distance of 150 mm from center line in x-direction.

In order to minimize the calculation time while ensuring sufficient accuracy, a graded mesh of 3.18 m 20B) in x-direction and 2.752m (≈17B) in y-direction was adopted. The benefits of the graded mesh are that a large number of small elements are present at the area of large deformation near the edge of the load, a large change in element aspect ratio is not present at the soil-geosynthetic interface, and a small number of elements are present near the model edges where occurrence of changes are not many. Mesh/grid local refinement is done to capture the stress/strain gradient around the pre-defined nodes on horizontal and axisymmetric axis. Convergence test of finite element model is important because it confirms that a fine enough element discretization has been used to capture the desired responses around the node of interest.

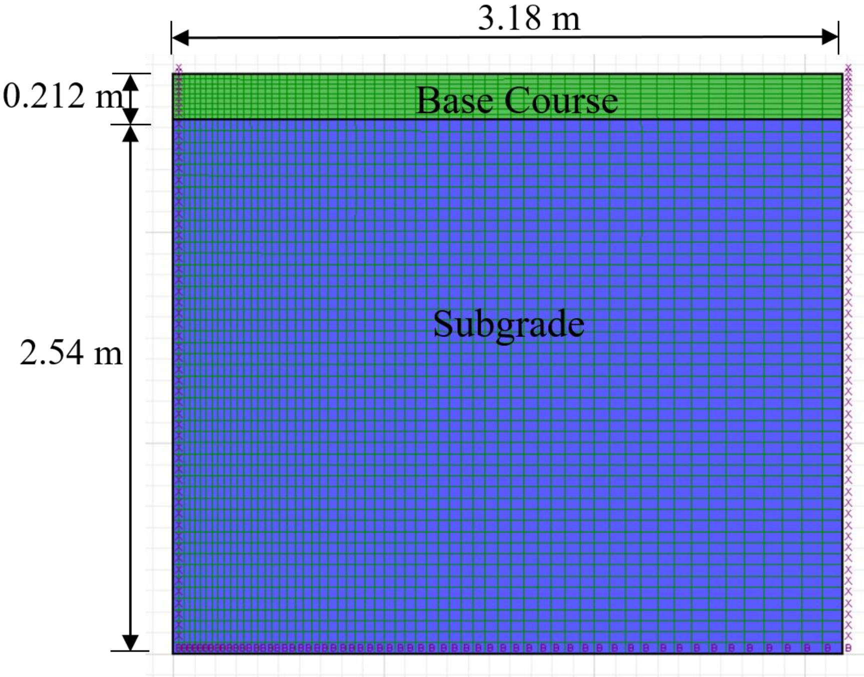


Figure 2 Graded mesh geometry with pavement layers and dimensions used in FLAC2D

4 MATERIAL PROPERTIES AND LOAD APPLICATION

Poor subgrades, good aggregate bases and marginal aggregates are considered in the study, properties of these materials are presented in Table 1. As the availability of the good quality aggregates for construction of unbound bases in some of the regions such as north-eastern parts of Indian sub-continent and many other parts of the world, marginal aggregates are used. The elastic modulus of the base courses depends on the quality of aggregate, thickness of the base layer and modulus of the layer over which it is constructed, however in the case of good aggregate bases the elastic modulus equal to 100 MPa is typically considered. In this study, marginal aggregates are considered by assuming a low elastic modulus equal to 50 MPa. Both the subgrade soil and base courses are assumed to follow Mohr-Coulomb model. The thickness of the base course and the subgrade soil considered are equal to 212 mm and 2540 mm, respectively.

Table 1 Properties of the subgrades and base courses used in the analysis

Property	Poor subgrade soil (PSG)	Marginal aggregate base course (MBC)	Good aggregate base course (GBC)
Material model	Mohr Coulomb	Mohr Coulomb	Mohr Coulomb
Mass density, kg/cu.m	1900	2200	2200
Friction angle Φ, deg	0	40	40
Cohesion, kPa	30	0	0
Elastic modulus, MPa	10	50	100
Poisson's ratio	0.33	0.25	0.25
Dilation angle, Ψ, deg	0	20	20

The structural element cable is used to represent geogrid reinforcement in the pavement model. Three types of reinforcement with different elastic modulus are considered to study the effect of reinforcement stiffness on the performance. Table 2 gives the properties of reinforcement considered in the study. Number of segments of the cable element used are 100, which ensured to have at least one segment in each zone. The reinforcement segment at the axis of symmetry is anchored to the boundary to arrest horizontal movement. This replicates field condition of the reinforcement.

Table 2 Properties of cable element used in the analysis

SNo.	Property	Value		
		Reinforcement 1	Reinforcement 2	Reinforcement 3
1	Young's modulus, MPa	146	1460	14600
2	Axial stiffness, kN/m	292	2920	29200
3	Area, sq.m	0.002	0.002	0.002
4	Bond stiffness kbond, N/m/m	5e9	5e9	5e9
5	Bond strength sbond, N/m	1.02E10	1.02E10	1.02E10
6	Tensile strength, N	2E4	2E4	2E4
7	Bond friction angle	35°	35°	35°
8	Perimeter, m	2.04	2.04	2.04

In the analysis, an initial gravity stress (corresponding to no applied load on the pavement) was applied on each element. Then a downward velocity was imposed on seven grid points representing the half width of the rare axle tyre set impression of the vehicle 160 mm. A constant downwards velocity of 2.5×10^{-6} m/step and 1×10^{-6} m/step are adopted for the case of a unreinforced and reinforced roadways, respectively. Unpaved pavement model was validated by comparing the vertical displacement and vertical stress obtained under static analysis using the FLAC2D program to that reported by Benmebarek et al. 2013 with similar conditions of simulation. The results obtained were found to agree with the results of Benmerbarek et al. 2013. Fig. 3 shows the comparison of the results.

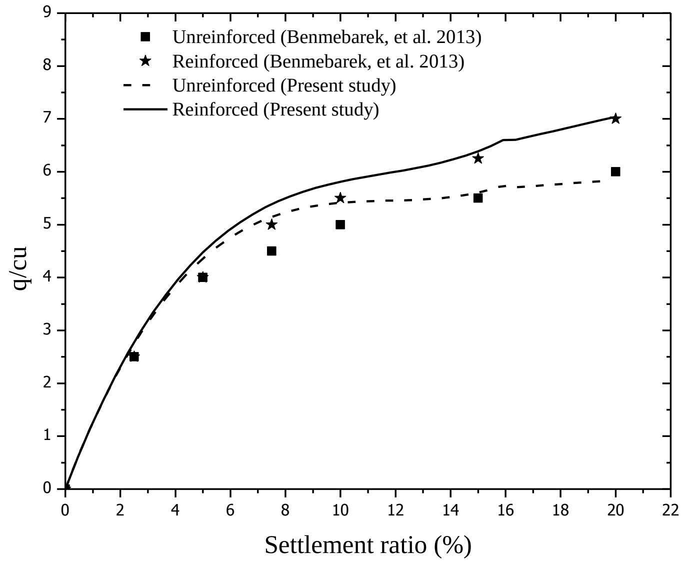


Figure 3 Plot showing comparison of settlement ratio and normalised load of present study with literature

5 RESULTS AND DISCUSSION

5.1 Reinforcement effect and Improvement

Figure 4 shows two cases of unreinforced pavement, one with good aggregate base course and the other one with marginal aggregate base course. It is observed the bearing pressure increases with the increase in settlement ratio. Pavement with good aggregate base course exhibit higher bearing pressure in comparison with that of marginal aggregate base course. Pavement with marginal aggregate base course is considered for reinforcement. Fig.5 show the variation of bearing pressure with settlement ratio for unreinforced pavement with marginal base course and reinforcement with different stiffness. Inclusion of reinforcement in the form structural element cable with different stiffness increased the bearing pressure. Higher stiffness (i.e., 29200 kN/m) showed higher bearing pressure in comparison with the other cases considered. Reinforcement benefit may be quantified based on the term *improvement factor*. The improvement factor may be defined as the ratio of bearing pressure under the footing resting on reinforced layered system at a given settlement, s, to that under the footing resting on unreinforced layered system at the same footing settlement. Table 3 gives the improvement factors for three types of reinforcements under consideration. In the case of reinforcement with stiffness equal to 292 kN/m, this factor varies from 1.02 to 1.15 in corresponding to settlement ratios range from 2% to 16%. Similar trend is observed in other two cases of reinforcement. At higher settlement ratio (equal to 16%), higher improvement factor (equal to 1.15) is observed and also for the reinforcement-3 with stiffness 29200 kN/m the improvement factor found to vary from 1.03 to 1.28 at settlement ratios 4% to 16%. It is observed from the values of improvement factors that a marginal aggregate based pavement with reinforcement stiffness 2920 kN/m and above is better in comparison with that of a pavement with good aggregate base course without reinforcement.

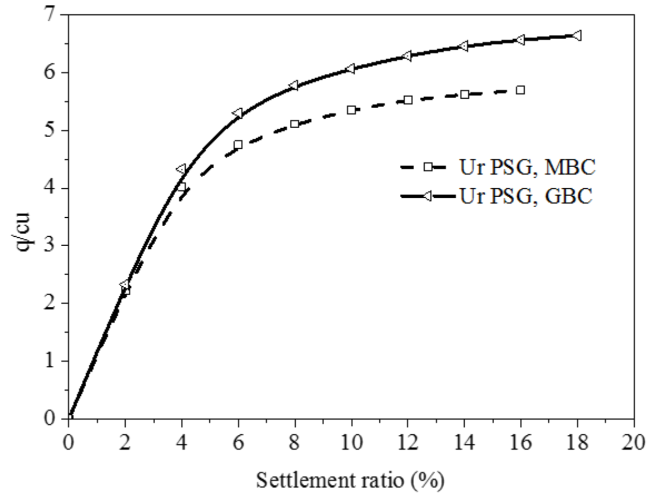


Figure 4 Variation of bearing pressure with settlement ratio for unreinforced pavement with good base course and marginal base course

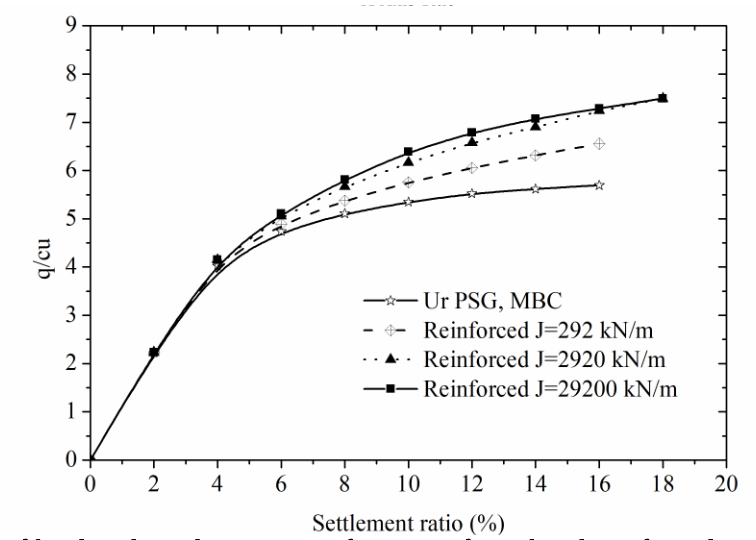


Figure 5 Variation of load with settlement ratio for unreinforced and reinforced pavement with marginal base course

Table 3 Improvement factors for good base course and reinforcements with different stiffness with respect to marginal aggregate base course at different settlement ratios

S No.	Settlement ratio, %	Improvement factor			
		Good base course	Reinforcement-1	Reinforcement-2	Reinforcement-3
1	4	1.08	1.02	1.03	1.03
2	8	1.13	1.06	1.11	1.14
3	12	1.14	1.1	1.20	1.24
4	14	1.15	1.13	1.23	1.26
5	16	1.16	1.15	1.27	1.28

Fig. 6 show the variation of axial force in reinforcement in three types of reinforcement at the settlement ratios of 8%, and 16%. Axial force in reinforcement found to increase with increase in settlement ratio and also with increase in reinforcement stiffness. At a settlement ratio of 16% (Fig. 6 c) axial force in reinforcement becomes almost zero beyond a horizontal distance of 1.25 m for all the three types of reinforcements, however for lower stiffness reinforcement, the axial force becomes close to zero at a horizontal distance of 0.5 m only. This indicates that higher stiffness (J = 29200 kN/m) reinforcement spreads the forces over a wide distance from loading point in comparison with that of lower stiffness (J = 292 kN/m) reinforcement particularly at greater settlement ratios (16%).

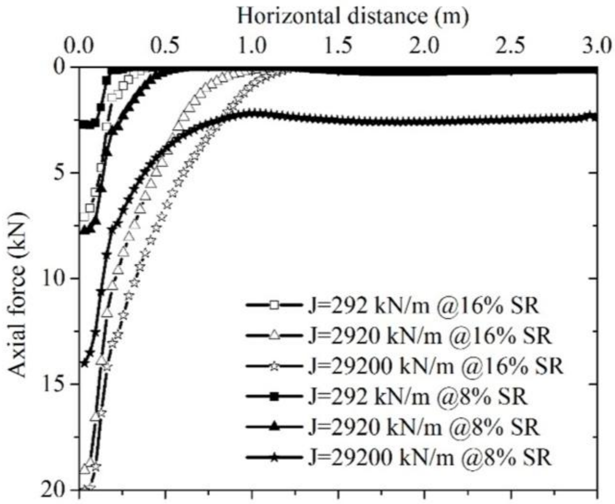
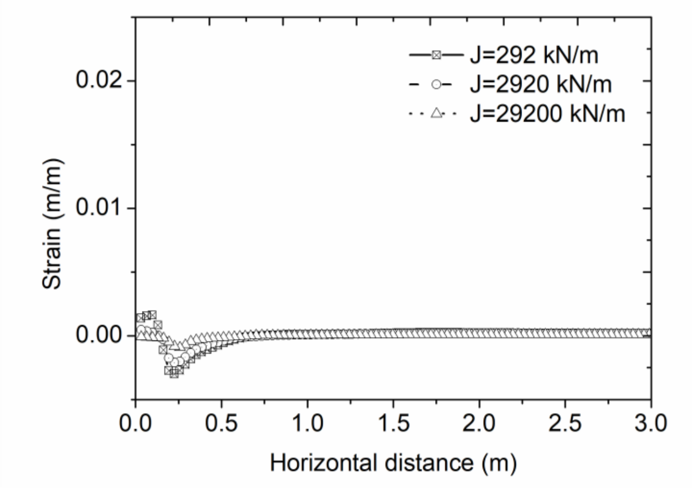
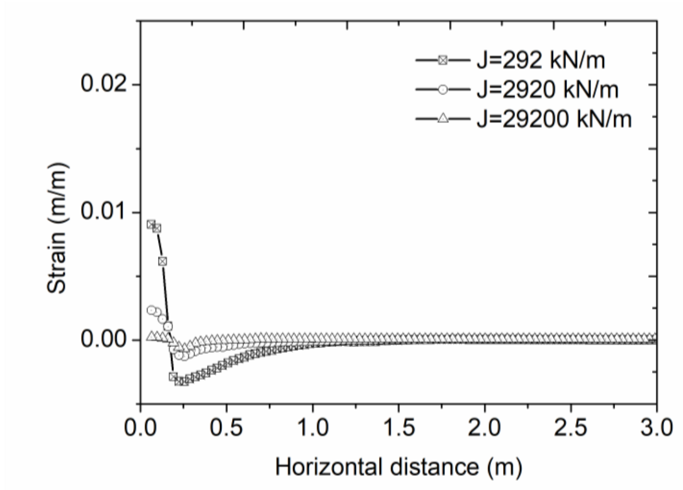


Figure 6 Variation of axial force in reinforcement with horizontal distance at settlement ratio of 8% and 16%

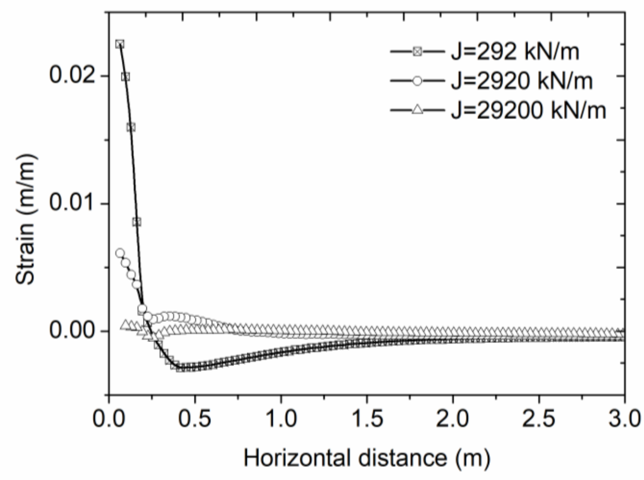
Fig. 7 a, b, and c show the variation of axial strain in the reinforcement with horizontal distance at settlement ratio of 4%, 8%, and 16% respectively. Strain in reinforcement increases with increase in settlement ratio. It is evident from figures, that at 4% settlement ratio, strain in the reinforcement is very nominal whereas at 16% settlement ratio it is significant and spreads over a horizontal distance of 1.5 m. Higher stiffness (J = 29200 kN/m) reinforcement exhibited lower strains at all levels of settlement ratios in comparison with that of lower stiffness (J = 292 kN/m) reinforcement. Change in sign of reinforcement strain near the edge of loading indicates formation of mechanism leading to the occurrence of failure.



(a)



(b)



(c)

Figure 7 Variation of axial strain in reinforcement with horizontal distance at settlement ratio (SR) of (a) 4%, (b) 8%, and (c) 16%

As the reinforcement with higher stiffness shown better performance in terms of improvement factors, the vertical stress profile with depth is observed for unreinforced case and reinforced case with reinforcement stiffness equal to 29200 kN/m. Figure 8 show the variation of vertical stress under loading with depth in unreinforced and reinforced pavement system at different levels of settlement ratios. Higher vertical stress found with reinforcement in comparison with unreinforced case. The difference in vertical stress between reinforced and unreinforced case is more at higher settlement ratio (16%) in comparison with that of lower settlement ratio (4%) up to a depth of 1.5 m and more so at the surface. From the surface to up to a depth of 1.0 m to 1.5 m vertical stress under the plate decreases after that it becomes almost constant. The slope of vertical stress curve is steep in base course layer in comparison with that in soil subgrade and the change is clearly seen at the interface.

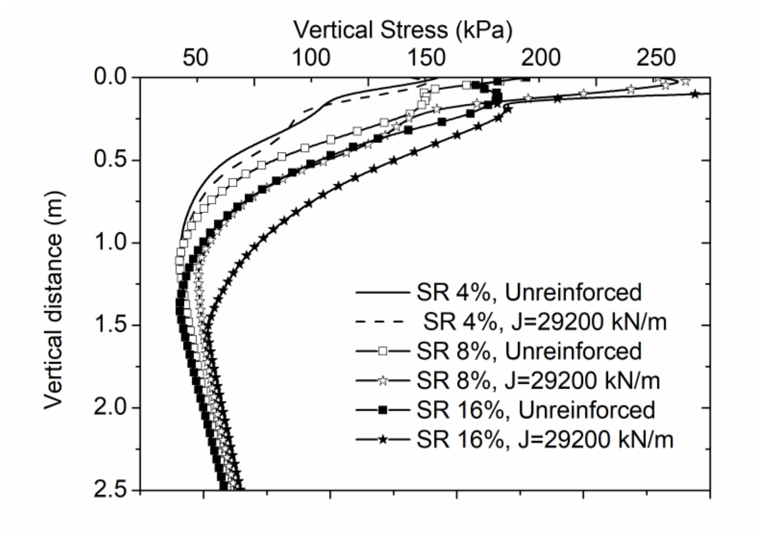


Figure 8 Variation of vertical stress with depth in unreinforced and reinforced pavement system at different levels of settlement ratio (SR)

5.2 Subgrade profile at different settlement ratio

Fig. 9 show the variation of vertical stress on the subgrade top at 4% and 16% settlement ratios both unreinforced and reinforced cases. Unreinforced case show lower vertical stress (58 kPa) in comparison with that of reinforced case (98 kPa) at the same settlement ratio of 16% and similar trend observed at other settlement ratios. Within a horizontal distance of 0.5 m from center, vertical and shear stress becomes constant almost zero. Fig. 10 show shear stress variation along the subgrade top at settlement ratios of 4% and 16% for both reinforced and unreinforced cases. Higher shear stresses (200 kPa) observed in case of reinforced base in comparison with that of unreinforced base (160 kPa) particularly at higher settlement ratio (16%). Shear stress become zero beyond 0.375 m from center for both the cases under consideration at different levels of settlement ratios.

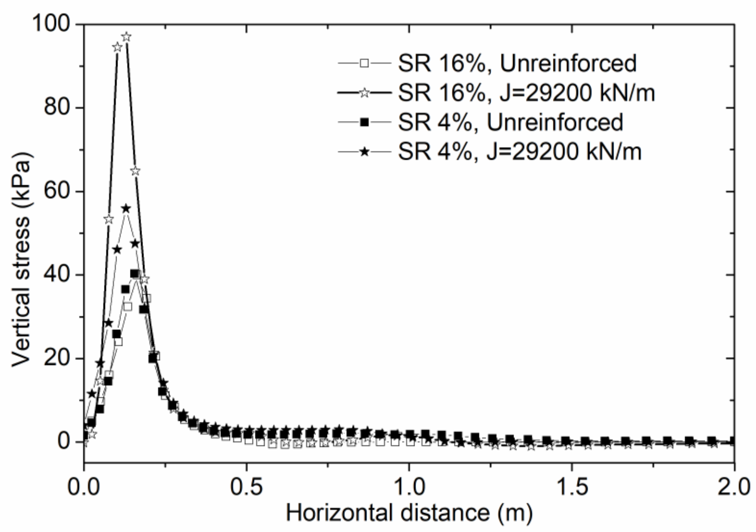


Figure 9 Vertical stress profile along the subgrade top at 4% and 16% settlement ratios of unreinforced and reinforced pavement system

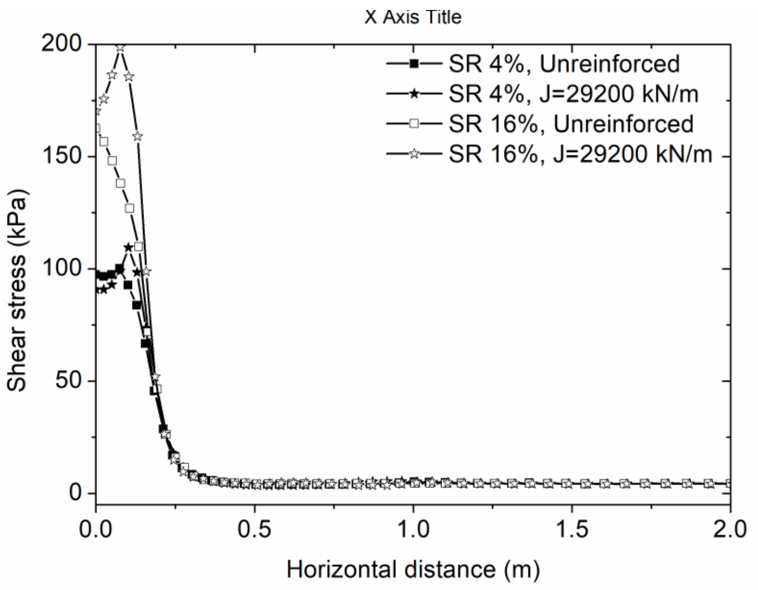


Figure 10 Shear stress profile along the subgrade surface at 4% and 16% settlement ratios with and without reinforcement

6 CONCLUSIONS

From the numerical analysis of unpaved pavement two layered system with the selected layer thickness and materials without and with reinforcement using FLAC2D program following can be concluded.

- In places where good aggregate is not available, it can be an option to reinforce marginal aggregate base course with planer reinforcement having enough stiffness.
- Axial force and strain in reinforcement become zero beyond a distance of 1.5 m from center indicating the contribution of reinforcement in distributing the effect of load over wide area.
- Beyond a distance of 0.5 m from the center of loading both vertical and shear stress on the subgrade top become zero indicating the high concentration of stresses close to the loading.

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