

# Finite element modeling of unbound granular pavements considering the effect of realistic moving loads

Piyush Punetha, Sanjay Nimbalkar

School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, Australia,  
[Sanjay.Nimbalkar@uts.edu.au](mailto:Sanjay.Nimbalkar@uts.edu.au)

**ABSTRACT:** To develop a mechanistic approach to pavement design, a comprehensive evaluation of the response of unbound granular pavements under realistic moving loads is paramount. With this objective, the behavior of an unbound granular pavement under moving loads is investigated using three-dimensional finite element (FE) simulations. The FE model of pavement is employed to gain detailed insights into the variation of tire-pavement contact pressure, stresses, strains and displacement. A parametric study is performed to examine the influence of material properties and vehicle loading characteristics on pavement performance. The results show that the tire-pavement contact pressure, surface deflection and stresses increase significantly with rising axle loads. The FE predictions are also compared with results from multilayer elastic analysis (MLEA), a method commonly used in routine engineering practice in Australia. The comparison reveals that MLEA significantly underestimates pavement response. The findings from this study underscore the importance of considering realistic moving loads and highlight the advantages of FE analysis for more accurate prediction of pavement response.

**KEYWORDS:** Finite element modeling, unbound granular pavements, moving load.

## 1 INTRODUCTION

Unsurfaced unbound granular pavements are commonly constructed in low-traffic areas, particularly in rural and remote regions where budget constraints prohibit the use of paved roads. Despite low traffic volume, these pavements often support the movement of heavy vehicles, which accelerate their deterioration due to increased deformation of granular materials and subgrade soil. This deterioration poses safety risks for road users and necessitates maintenance to restore pavement geometry to acceptable levels, incurring substantial costs.

A key factor contributing to the rapid deterioration of these pavements is the use of oversimplified design methods (Austroads, 2024), which fail to capture the complex behavior of unbound granular materials and subgrade soils under moving loads. Moreover, the current practice of representing tire loading by uniformly distributed pressure is unrealistic since the tire-pavement contact stress varies significantly within the contact zone (Punetha & Nimbalkar, 2025a). Therefore, an advanced mechanistic design approach is required which accounts for realistic tire-pavement contact stress variations and better reflects actual pavement behavior. Developing such improved methods necessitates a comprehensive analysis of pavement performance under realistic moving loads.

The finite element (FE) method has emerged as a powerful tool for analyzing pavement response under various boundary conditions and material types. Researchers have employed two-dimensional and three-dimensional (3D) FE models of pavements to study their response under different loading scenarios (Ali et al., 2009, Kettil et al., 2007, Pooni et al., 2020, Punetha & Nimbalkar, 2025b). Tire loading in previous FE analyses has often been simulated using simplified methods, such as application of time-varying stress pulses or translation of tire imprints on pavement surface (Elseifi et al., 2006, Ghadimi et al., 2016, Saad et al., 2005, Wang & Al-Qadi, 2009). However, limited studies have incorporated realistic movement of tires (including both translation and rolling) or adequately captured the tire-pavement interaction. In addition, research has concentrated primarily on paved roads with less attention given to the behavior of unsurfaced pavements.

This study examines the behavior of unsurfaced unbound granular pavements subjected to realistic moving loads (involving both translation and rolling of tires) using 3D FE analyses. The importance of considering realistic tire movement is highlighted by comparing pavement response

predicted using this method with that from a simplified approach, in which the moving load is simulated by translating rectangular plates. The sensitivity of pavement response to variations in axle load and subgrade type is evaluated by conducting parametric study. The response predicted from finite element analysis (FEA) is also compared with that from multilayer elastic analysis (MLEA) carried out using CIRCLY software, which is commonly used in Australia for pavement analysis and design (Mincad Systems, 2017). The main objectives of this study are to highlight the importance of considering realistic moving loads for accurate prediction of pavement response and to demonstrate the benefits of 3D FEA over conventional MLEA based approaches.

## 2 FINITE ELEMENT MODEL DEVELOPMENT

A 3D model of an unsurfaced unbound granular pavement is developed using the FE package Abaqus (see Figure 1). The pavement structure comprises 150 mm thick base and subbase courses overlying 3,000 mm thick subgrade. The bottom boundary of the model is completely restrained while the side boundaries are restrained in lateral orthogonal ( $x$  and  $y$ ) directions. The pavement mesh comprises 260,092 elements of type C3D8R (8-noded 3D brick elements with reduced integration). A finer mesh is used in the tire-pavement contact zone that gradually becomes coarser towards the boundaries. A single-axle dual tire (SADT) assembly (or standard axle) is considered, with each tire modeled to include a rubber carcass, rim, treads, 1 radial ply, and 2 steel belts (Wang et al., 2012).

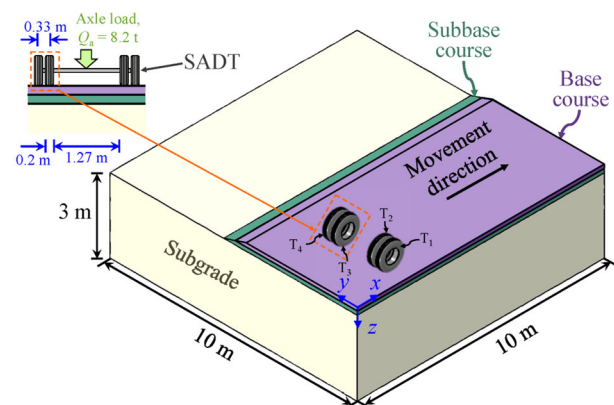


Figure 1. 3D model of unsurfaced unbound granular pavement.

The analysis is carried out in three phases. In the first phase, gravity loads are applied to the pavement structure to establish the initial stress state. The SADT assembly is activated in the second phase, and it is translated and rolled along the longitudinal direction ( $x$  direction) in the third phase. The tire motion is simulated by applying displacement and rotation values at reference points located at the center of each tire. These reference points are connected to the rims using multi-point constraints (Dassault Systèmes, 2018). Only free-rolling conditions have been considered in this study.

### 3 RESULTS AND DISCUSSION

#### 3.1 Effect of the moving load simulation method

This section highlights the importance of simulating realistic moving loads for more accurate prediction of pavement response. The moving loads are simulated using two distinct approaches. The first approach involves the translation of rectangular plates, representing tire-pavement contact, over the pavement surface. The dimensions of the plates are selected to achieve a uniform tire-pavement contact pressure ( $\sigma_p$ ) of 750 kPa under 8.2 t (80 kN) axle load (Huang, 2004). The second approach involves the translation and rolling of actual tires in a SADT assembly. The axle load and tire inflation pressure are considered 8.2 t and 750 kPa, respectively, for second approach. The tire-pavement interaction in both methods is simulated using the Coulomb friction model with ‘hard’ normal contact and penalty friction algorithm-based tangential contact (Dassault Systèmes, 2018). The base, subbase and subgrade layers are assumed to behave elastically, with resilient moduli of 500 MPa, 400 MPa and 140 MPa, respectively (Punetha & Nimbalkar, 2025a). Poisson’s ratio for base, subbase and subgrade are taken as 0.35, 0.35 and 0.4, respectively.

Figure 2 shows a comparison of vertical displacement at the top of base layer predicted using both approaches when the SADT assembly reaches the center of the model ( $x = 5$  m). The results indicate that the vertical displacement is greater when realistic tire motion is simulated. Specifically, the peak vertical displacement is underestimated by 16% when moving loads are simulated using the first approach (rectangular plate translation) compared to the second approach (real tire translation and rolling). This discrepancy can be attributed to differences in motion (translation only and translation with rolling), contact shape (rectangular and oval) and distribution of tire-pavement contact stresses (uniform in the case of rectangular plates and non-uniform in real tire case).

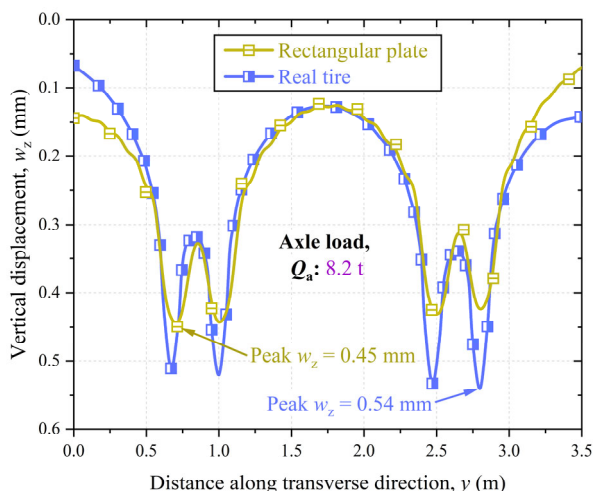


Figure 2. Variation of vertical displacement along transverse direction for two moving load simulation methods.

It is evident from the results that the incorporation of realistic moving loads is essential for accurate prediction of pavement response. Therefore, subsequent analyses are carried out using the SADT with real tires (involving both translation and rolling). In addition, the results presented in this section were derived from elastic analysis, however, geomaterials exhibit elastoplastic behavior. Hence, the mechanical behavior of granular layers and subgrade is modeled using elastoplastic constitutive models in next sections. The material parameters adopted for subsequent analyses are listed in Table 1. It should be noted that a stiffer subgrade was assumed in section 3.1, whereas a softer subgrade is considered in the subsequent sections to represent a worst-case scenario. The influence of subgrade type is discussed separately in Section 3.4.

Table 1. Material parameters used in the finite element analysis.

Layer	Base	Subbase	Subgrade
Constitutive model	DP	DP	MC
Resilient modulus, $E_r$ (MPa)	500 <sup>*</sup>	400 <sup>‡</sup>	10 <sup>#</sup>
Poisson’s ratio, $\nu$	0.35 <sup>†</sup>	0.35 <sup>†</sup>	0.4 <sup>†</sup>
Apparent cohesion, $c'$ (kPa)	9.6 <sup>*</sup>	9.9 <sup>*</sup>	10 <sup>#</sup>
Friction angle, $\phi'$ (°)	48.6 <sup>*</sup>	45 <sup>*</sup>	20 <sup>#</sup>
Dilation angle, $\psi$ (°)	15 <sup>†</sup>	15 <sup>†</sup>	1 <sup>†</sup>

<sup>\*</sup>determined from static and cyclic triaxial tests (Lee et al., 2019); <sup>†</sup>assumed values; <sup>‡</sup>taken from Austroads (2024); <sup>#</sup>sourced from Sharp & Booker (1984); DP: linear Drucker-Prager yield criterion with an isotropic hardening law and a non-associated flow rule; MC: Mohr-Coulomb yield criterion with a non-associated flow rule.

#### 3.2 Importance of considering moving loads

Figure 3 shows a comparison of the stress paths experienced by a soil element in subgrade located at a depth of 500 mm below base top under static and moving load conditions. In the static load case, the tire is activated but remains stationary. It can be observed that under moving loads, the shear stress direction reverses from positive to negative as the tire assembly rolls over the pavement. This reversal in the direction of shear stress causes principal stress rotation, which can significantly affect the behavior of soil and granular materials (Gräbe & Clayton, 2009, Punetha & Nimbalkar, 2022, 2023). Conversely, the direction of shear stress for the static load case remains constant, resulting in a fixed orientation of principal stresses. This finding demonstrates that the static load case fails to replicate realistic stress paths which involve principal stress rotation. Therefore, incorporating moving loads is essential for more accurate estimation of stress distribution.

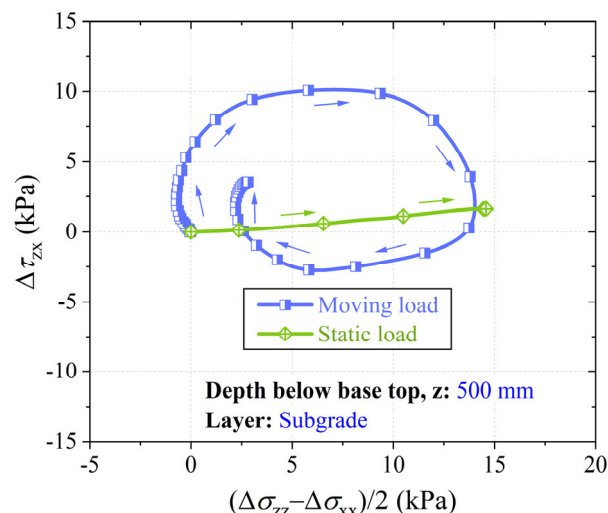


Figure 3. Stress path experienced by a soil element in subgrade located at a depth of 500 mm below base top.

The subsequent sections investigate the behavior of unsurfaced unbound granular pavements under varying axle loads and subgrade conditions.

### 3.3 Influence of axle load

The axle load ( $Q_a$ ) is varied from 8.2 t to 12.2 t (120 kN) to investigate its influence on tire-pavement contact stress, surface deflection and stress distribution. Figure 4 illustrates the variation in  $\sigma_p$  along the transverse direction beneath tire  $T_3$  for three different  $Q_a$ . It is apparent that the contact pressure increases with an increase in  $Q_a$ . Specifically, the peak  $\sigma_p$  increases by 18% when  $Q_a$  rises from 8.2 t to 12.2 t. In addition, the pressure distribution changes significantly with  $Q_a$ . At lower  $Q_a$ , peak contact pressure occurs near the middle portion of the tire, whereas at higher loads, it shifts towards the edges.

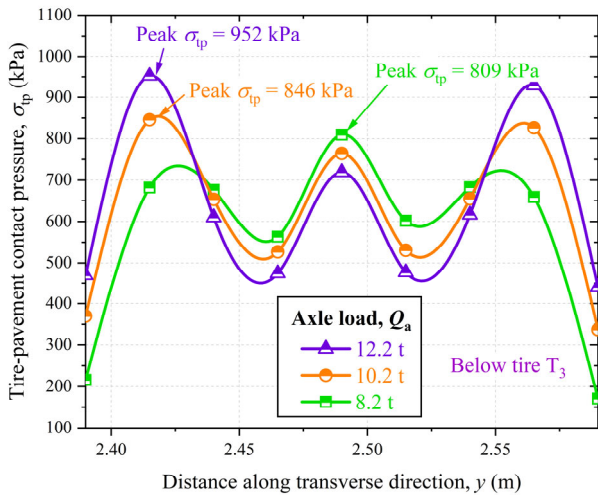


Figure 4. Variation of tire-pavement contact pressure along transverse direction at different axle loads.

Table 2 shows the variation of peak pavement deflection and peak vertical stress at subgrade top with  $Q_a$ . It can be observed that the peak pavement deflection rises by 49% on increasing  $Q_a$  from 8.2 t to 12.2 t. This increase is ascribed to the elevated contact pressure levels, which amplify the stresses transmitted to the pavement layers. For instance, the peak vertical stress at subgrade top rises by 77% when  $Q_a$  escalates to 12.2 t. This increase in stress contributes to their accelerated deterioration under movement of heavy vehicles.

Table 2. Variation of peak pavement deflection and subgrade stress with axle load.

Axle load (t)	Peak pavement deflection, $w_{z,p}$ (mm)	Peak vertical stress at subgrade top, $\sigma_{z,p}$ (kPa)
8.2	3.51	57.5
10.2	4.34	68.6
12.2	5.22	102

### 3.4 Influence of subgrade type

This section examines the effect of subgrade type on contact pressure and critical strains within the pavement. Two types of subgrade are considered: soft and stiff. The properties of soft subgrade are provided in Table 1. The values of resilient modulus, Poisson's ratio, apparent cohesion, friction and dilation angles for stiff subgrade are taken as 140 MPa, 0.4, 10 kPa, 32° and 2°, respectively (Punetha & Nimbalkar, 2025a). Figure 5 illustrates a comparison of peak  $\sigma_p$  and vertical strain at the top of subgrade for both cases. It can be observed that the presence of a stiffer subgrade leads to an increase in  $\sigma_p$ . In addition, the peak vertical strain at the top of soft subgrade is approximately 7.8 times greater than that observed in the stiff

subgrade. Although the contact pressure is slightly higher for stiff subgrade, its greater stiffness and strength nullifies the effect of increased stresses, leading to a significantly lower deformation compared to soft subgrade.

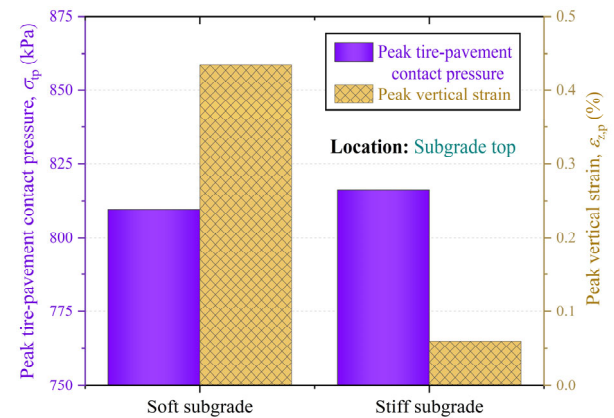


Figure 5. Influence of subgrade type on tire-pavement contact stress and vertical subgrade strain.

## 4 COMPARISON WITH MULTI-LAYER ELASTIC ANALYSIS

This section highlights the benefits of using FEA for more accurate prediction of pavement response compared to MLEA. In MLEA, the pavement is idealized as a system of multiple elastic layers, and a stress function is assumed for each layer that satisfies the compatibility equation, as well as boundary and continuity conditions (Huang, 2004). The stresses and displacements in this system under a circular loaded area are then determined by solving the equations derived from the theory of elasticity (Burmister, 1945).

Figure 6 shows a comparison of the peak vertical strain predicted using FEA and MLEA at different depths. It is apparent that MLEA underpredicts the vertical strain values by 39–60% in comparison to FEA. This discrepancy can be attributed to the fact that the tire load in MLEA is represented as a uniformly distributed static load, which fails to capture realistic stress paths generated under moving loads. In addition, material behavior in MLEA is assumed elastic, which overlooks plastic deformations and resulting stress-redistribution. These findings highlight the limitations of MLEA and demonstrate that FEA offers a more reliable approach for evaluating pavement behavior.

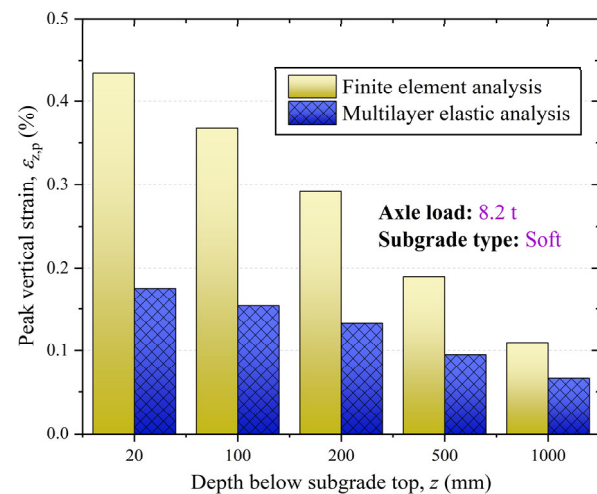


Figure 6. Peak vertical strain predicted using FEA and MLEA.

## 5 MODEL VALIDATION

The accuracy of the FE model in predicting pavement response is assessed by comparing its output with data obtained from an accelerated loading facility (ALF) by Vuong et al. (1996). The material parameters used in the simulations for base ( $E_r = 332$  MPa;  $\nu = 0.4$ ;  $c' = 9.6$  kPa;  $\phi' = 30^\circ$ ), subbase ( $E_r = 200$  MPa;  $\nu = 0.4$ ;  $c' = 10.4$  kPa;  $\phi' = 27.1^\circ$ ) and subgrade ( $E_r = 50$  MPa;  $\nu = 0.45$ ;  $c' = 10$  kPa;  $\phi' = 20^\circ$ ) are adopted from Pooni et al. (2020). Figure 7 illustrates a comparison of the residual vertical displacement at the pavement surface predicted using FEA with the data collected from ALF. It is evident that the predicted results are in good agreement with ALF data, confirming the reliability of the modelling approach.

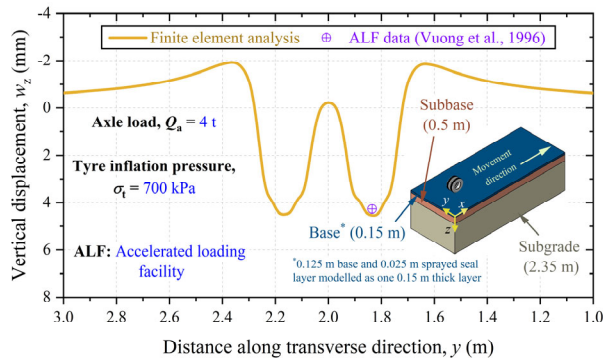


Figure 7. Comparison of FE predictions with ALF data [modified after Punetha & Nimbalkar (2025a)]

## 6 CONCLUSIONS

This study investigated the behavior of unsurfaced unbound granular pavements subjected to realistic moving loads. The findings demonstrate that the simulation of moving loads using simplified methods (e.g., translating rectangular plates) leads to an underestimation of pavement deflection, highlighting the importance of considering realistic tire movement. Results from parametric analyses reveal that the tire-pavement contact pressure, the vertical stress at subgrade top and the pavement deflection increases by 18%, 77% and 49%, respectively on increasing axle load from 8.2 t to 12.2 t. This study also highlighted that MLEA substantially underestimates pavement deformation compared to FEA due to its inability to capture realistic moving loads and elastoplastic material behavior. Therefore, 3D FEA should be preferred over MLEA for more accurate pavement analysis and design.

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