

COMPARISON BETWEEN THE SIMPLIFIED AUSTROADS SUBLAYERING APPROACH AND THE EXACT NONLINEAR SOLUTIONS FOR THE UNBOUND FLEXIBLE PAVEMENTS

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ABSTRACT

In the mechanistic pavement design, it is common practice that the coarse and fine grained materials are modelled as linear elastic materials. The main reason for this is to use a simple set of parameters to represent each layer which in this case are the elastic modulus and Poisson ratio. However, it is well known that the unbound coarse granular materials and the fine grained subgrade materials behave nonlinearly under the traffic loading.

The Australian mechanistic empirical design method (AUSTROADS) uses a simplified approach to account for the nonlinear behaviour of the unbound coarse and fine grained materials. In this paper the Austroads quasi-linear analysis is compared with the exact nonlinear analysis to examine the validity of this approach. The Austroads quasi-linear analysis provided better solutions than the linear elastic analysis without sublayering, however, it needs some adjustment to provide better match with the exact nonlinear analysis solution.

KEY WORDS

nonlinear, sublayering, mechanistic, design, base

INTRODUCTION

The unbound granular layers of the pavement undergo compaction during the construction of pavements and subsequent repeated loading of traffic during early stages of its life. This causes the unbound layers to shake down to a resilient (elastic) state which has been mimicked in laboratory by triaxial testing, (1).

Although the responses have been found elastic, the behaviour has been observed nonlinear due to stress dependent moduli and Poisson's ratio (2). Various factors contribute for this nonlinearity in the responses (3)

The nonlinearity can simply be said to arise when the magnitude of response produced for the applied excitation fail to be proportional to the excitation. This nonlinear behaviour can be due to geometric if the body undergoes large deformations or due to the constitutive behaviour of the material within the body or occurs as a mixture of both geometric and material nonlinearities.

During the service life of pavements, one of the major factors causing nonlinear behaviour is the state of stress. As the level of loading on the pavement changes, the parameters such as resilient modulus which define the physical characteristics of the material changes.

Nonlinearity of unbound materials has been addressed by forming an appropriate constitutive relationship for the desired material; that is obtaining an expression for resilient (or elastic) modulus in terms of the stress or strain state of the material under loading coupled with physical properties of the material. Various models have been proposed in the literature to represent the resilient modulus of the unbound material under loading and at different environmental conditions. Changes in environmental conditions have been the most difficult variables to be incorporated in a model; seasonal frost conditions have significant effect on the resilient properties of the material (4).

The following are list of models proposed in the literature to characterize resilient modulus of unbound materials under loading.

k-theta model

The most commonly used nonlinear elastic model characterizing the behaviour of unbound material is k-theta model (5). The resilient modulus is given by:

$$M_r = k_1 * \left(\frac{\theta}{P_a} \right)^{k_2} \quad (1)$$

Where,

- M_r = resilient (Elastic) Modulus;
- k₁, k₂ = material parameters (constants);
- θ = bulk stress,
- Pa= atmospheric pressure

Deviator stress model

While the k-theta model is applicable for stress hardening of the material, characterizing the softening behaviour of fine-grained soil may be given by the deviator stress model.

$$M_r = k_3 * \left(\frac{\sigma_d}{P_a} \right)^{k_4} \quad (2)$$

Where,

k_3, k_4 = material parameters (constants);
 σ_d = deviator stress.

Although the k-theta model is simple and has been used in number of applications, the model can only represent very limited range of stress paths and it fails to address the importance of shear stress which has been found very to be very important in determination of permanent deformation of the material (6).

Octahedral universal model

Uzan (7) proposed a universal soil model based on stress invariant approach and introduced octahedral shear component into the k-theta model and subsequently normalised the stress components by atmospheric pressure to make those quantities dimensionless as in Equation 3.

$$M_r = k_1 * P_a * \left(\frac{\theta}{P_a} \right)^{k_2} * \left(\frac{\tau_{oct}}{P_a} \right)^{k_3} \quad (3)$$

Where, k_1, k_2, k_3 are material parameters;

θ = first stress invariant also it is called the bulk stress;

τ_{oct} = octahedral shear stress;

P_a = atmospheric pressure.

In the mechanistic pavement design, it is common practice that the coarse and fine grained materials are modelled as linear elastic materials. The main reason for this is to use a simple set of parameters to represent each layer which in this case are the elastic modulus and Poisson ratio. Another reason is the availability of multilayer linear elastic models that serve as the engine of the mechanistic empirical design. However, it is well known that the unbound coarse granular materials and the fine grained subgrade materials behave nonlinearly under the traffic loading. In this paper the Austroads quasi-linear analysis will be compared with the exact nonlinear analysis to examine the validity of this approach. The triaxial data of the unbound materials will be analysed and the constitutive nonlinear coefficients will be determined.

AUSTROADS SUBLAYERING APPROACH

The Australian mechanistic empirical design method (AUSTROADS) uses a simplified approach to account for the nonlinear behaviour of the unbound coarse granular and fine grained materials. In this approach, the unbound material is divided into five sublayers and the modulus for the base course is reduced incrementally by a factor (R) that depends on the modulus of the top layer of the base and the modulus of the subgrade. The reduction of the modulus is intended to correspond to the reduction of the stresses deeper in the pavement and therefore simulating the stress hardening of these materials. The reduction factor R is calculated as shown in Equation 4.

$$R = \left(\frac{Mr_{Top\ Base}}{Mr_{Top\ Subgrade}} \right)^{1/5} \quad (4)$$

For example, if the top modulus of the base shown in **Figure 1** is 400 MPa and the top modulus of the subgrade is 50 MPa and the thickness of the base course is 400 mm, the Austroads design method will divide the 400 mm base into 5 sublayers each 80 mm thickness and the modulus reduction factor is calculated according to Equation 4. In this case $R=1.516$, therefore the modulus of second sublayer equals the top modulus of the base (400 MPa) divided by 1.516 which equals 263.9 MPa and the modulus for the third sublayer equals the modulus of the second sublayer divided by 1.516 which is 174.1 MPa and so on until the fifth sublayer.

After carrying out the sublayering, the linear elastic analysis is applied on the pavement section to determine the pavement responses to the axle loads.

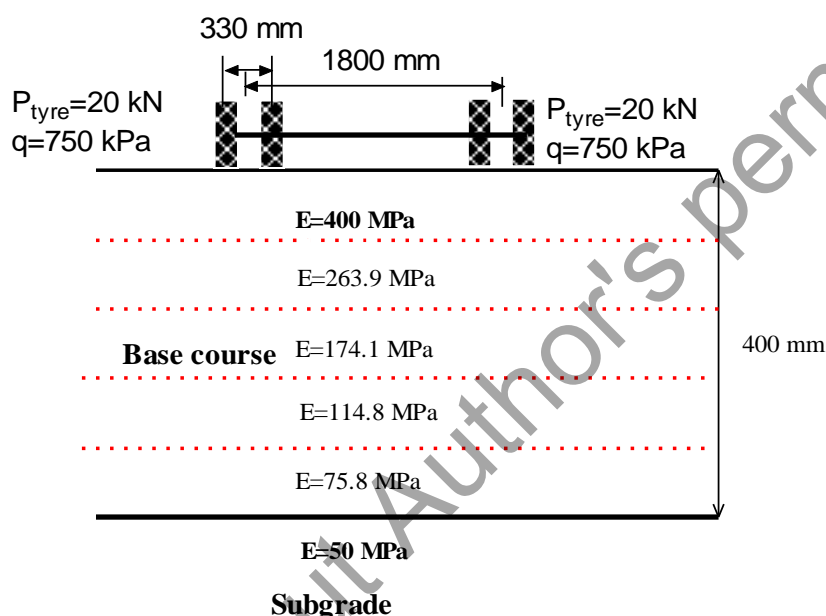


Figure 1 Austroads Sublayering Approach

BASE COURSE MATERIALS

The repeated triaxial test was carried out on three different types of base course materials, A, B and C. **Figure 2** shows the relationship between the normalised bulk stress (θ/Pa) and the measured resilient modulus for the base course materials, A, B, and C. The regression analysis was used to determine the k_1 and k_2 coefficients for the k-theta model.

For material A, $k_1 = 108.851$ and $k_2 = 0.7225$. **Figure 3** shows the goodness of fit of the suggested k-theta model for material A. Since the relationship between the measured and predicted resilient modulus are clustering on the 45° straight line, this indicates a perfect fit of the model. A similar analysis has been done on materials B and C. **Table 1** shows the k_1 and k_2 for the three different materials.

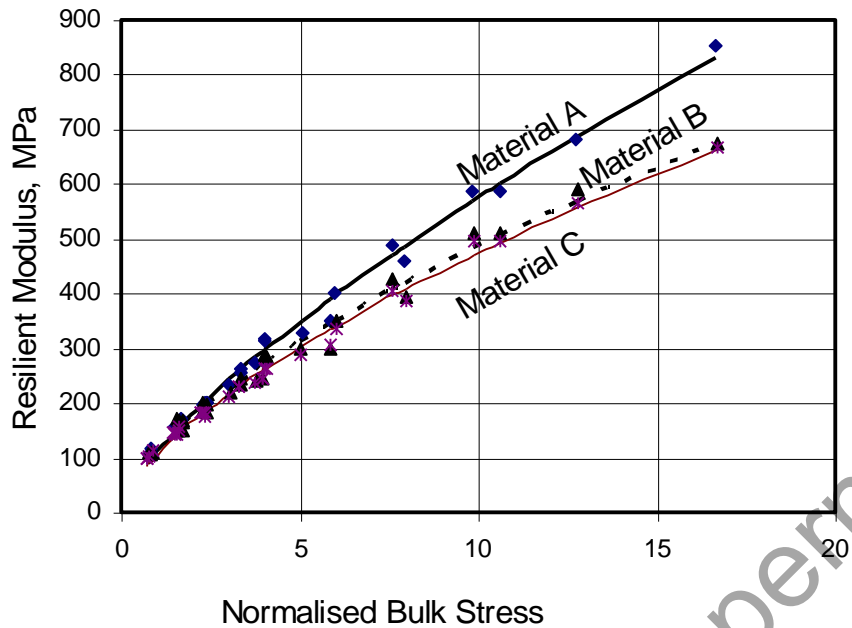


Figure 2 Relationship between resilient modulus and normalised bulk stress for different materials.

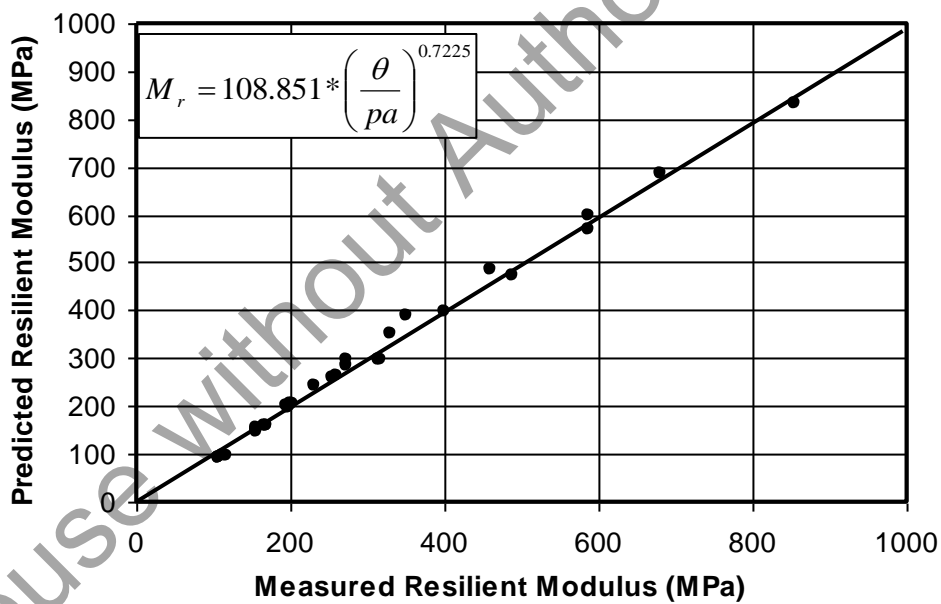


Figure 3 Relationship between predicted and measured resilient modulus for base course material A

Table1 The k-Theta model coefficients for the different base materials

| Base Material | k ₁ | k ₂ |
|---------------|----------------|----------------|
| A | 108.851 | 0.7225 |
| B | 110.384 | 0.6443 |
| C | 105.196 | 0.6535 |

PAVEMENT RESPONSE ANALYSIS

In this analysis a two-layer pavement was analysed under the standard axle load (80kN) as shown **Figure 1**. Three different scenarios were analyzed. In the first scenario, a base course with 400 mm thickness of material A was used with a subgrade of resilient modulus 103 MPa and Poisson ratio 0.45. For the other two scenarios materials B and C were used as the based course materials. For each scenario, the pavement responses were determined using three different types of analyses, linear elastic with no sublayering, exact nonlinear elastic and linear elastic with sublayering (Austroads). The vertical stresses, strains and bulk stresses were determined at different depths under the centre of one wheel and between the dual tyres for the three scenarios using the three different analyses.

Everstress multilayer elastic software was used for the linear with no sublayering and the exact nonlinear analysis (8). Circlly software was used to carry out the linear elastic analysis on the sublayered system (9). Circlly is provided with the subroutines that can carry out automatically the sublayering and assign the resilient modulus for each sublayer as explained before.

For the linear elastic analysis, an average resilient modulus based on the triaxial data was assigned to the unbound base course. The subgrade was assumed to be linear elastic in all the three analyses.

Figure 4 shows variation of the resilient modulus for the three analyses for first scenario. The linear elastic analysis assumes a constant modulus for the entire depth of the unbound material; however, the exact nonlinear and sublayering analyses vary the resilient modulus with depth. The Austroads sublayering system for the three scenarios provided the same resilient modulus as the exact nonlinear analysis at the mid depth of the unbound material as shown in **Figure 4**. Austroads sublayering approach underestimates the resilient moduli in the top half of the unbound material and overestimates the resilient moduli in the bottom half of the unbound base layer as shown in **Figure 4**.

Figure 4 represents the results for the first scenario, however, the other two scenarios provided similar trends but the results are not shown here in this paper because of the paper size limitation.

The Austroads sublayering approach provided better solution compared to the linear elastic without sublayering, however, it does not provide identical match with the exact nonlinear analysis. In this analysis all materials are assumed to be isotropic. In Austroads design, cross anisotropic properties for the unbound base and subgrade are assumed with anisotropy ratio of 2 (Anisotropy ratio = $\frac{E_V}{E_H}$, E_V is the vertical resilient modulus and E_H is the horizontal resilient modulus).

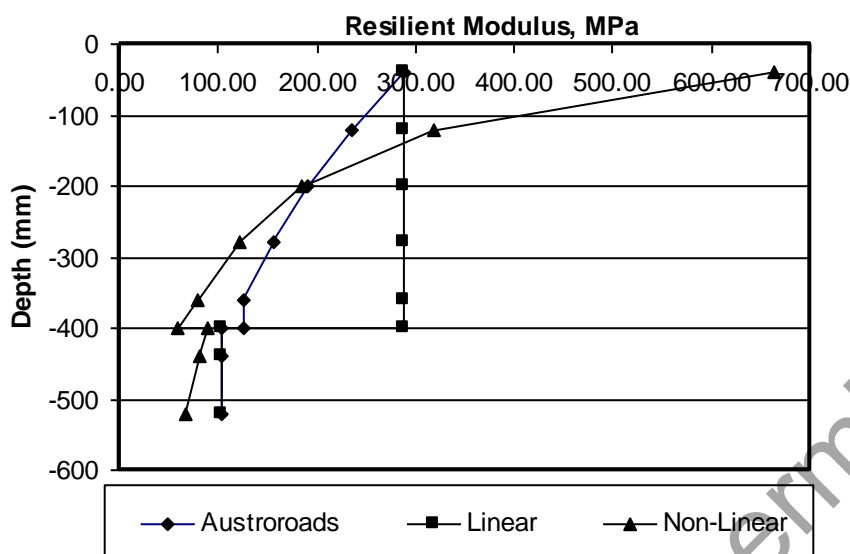


Figure 4 Comparison between the resilient moduli of the three analyses

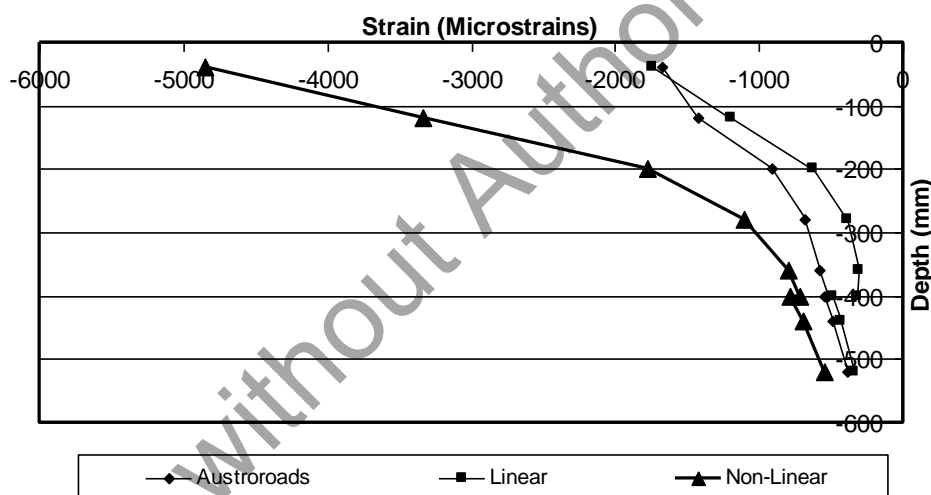


Figure 5 The vertical strain distribution with depth for the three analyses for the first scenario

Figure 5 shows the vertical strain distribution with depth for the three analyses for first scenario. It is obvious that the sublayering system provided slightly better solution than the linear elastic analysis without sublayering, however, it is still underestimating the vertical strains compared to the exact nonlinear analysis. The analyses of the other two scenarios provided the same results but they are not shown here because the size limitation of the paper.

CONCLUSIONS

The comparison between the linear elastic solution without sublayering, linear elastic with sublayering using Austroroads approach and the exact nonlinear analysis showed that the sublayering analysis provided better solutions than that without sublayering which are closer to the exact nonlinear analysis. The use of simplified Austroroads sublayering analysis with some minor adjustment such as using different degrees of anisotropy or using different function to change the modulus over the pavement depth can provide accurate solutions

which will make these kind of analysis more appealing to practitioners because it needs few input parameters and simple multilayer elastic software to carry out the design and analysis of pavement structure.

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REFERENCES

- 1) Werkmeister, S., A. R. Dawson, et al. (2004). "Pavement Design Model for Unbound Granular Materials." *Journal of Transportation Engineering* 130(5): 665-674.
- 2) Park, S.-W. and R. L. Lytton (2004). "Effect of Stress-Dependent Modulus and Poisson's Ratio on Structural Responses in Thin Asphalt Pavements." *Journal of Transportation Engineering*: 387-394.
- 3) Desai, C. S. and H. J. Siriwardane (1984). *Constitutive laws for engineering materials with emphasis on geological materials*, Prentice-Hall, Eaglewood Cliff, N.J.
- 4) Simonsen, E., V. C. Janoo, et al. (2002). "Resilient Properties of Unbound Road Materials during Seasonal Frost Conditions." *Journal of Cold Regions Engineering* 16(1): 28-50.
- 5) Hicks, R. G. and C. L. Monismith (1971). "Factors influencing the resilient properties of granular material." *Transportation Research Record* 345: 15-31.
- 6) Brown, S. F. and J. W. Pappin (1981). "Analysis of pavements with granular bases." *Transportation Research Record* 810: 17-23.
- 7) Uzan, J. (1992). "Resilient characterization of pavement materials." *International Journal for Numerical and Analytical Methods in Geo-mechanics* 16(6): 435-459.
- 8) Everstress version 5 for Windows software, Layered Elastic Analysis, Washington State Department of Transportation, March 1999
- 9) Wardle, L.J. (1977), *Program CIRCLY, User's Manual, Geomechanics Computer Program Number 2*. Division of Applied Geomechanics, Commonwealth Scientific and Industrial Research Organisation, Melbourne, Australia.