Mechanistic Design of Low Volume Road Structures

P. Kolisoja, A. Kalliainen & N. Vuorimies
Department of Civil Engineering, Tampere University of Technology, Tampere, Finland

ABSTRACT: This paper presents a new design approach for assessing the risk of excessive permanent deformation development in soft subgrade soil underlying a low volume road of thin structural layers exposed to heavy wheel loads i.e. Mode 2 rutting using the terminology defined in the EU-funded ROADEX project. The approach is essentially based on back-calculating the results of 3D Finite Element modelling produced with the PLAXIS software package in a way that allows obtaining the same result in terms of ultimate load carrying capacity of the subgrade soil by a simple hand-calculation procedure as would be obtained by sophisticated 3D FE modelling of the loading arrangement / road structure / subgrade soil combination in question.

KEY WORDS: Permanent deformation, rutting, subgrade, design, low volume road

1 INTRODUCTION

Low Volume Roads (LVRs) have generally received very little attention as concerns intentions to develop mechanistic pavement design approaches. Yet, the functional significance of the local road network should not be underestimated. More often than not, LVRs play an important role in providing the inhabitants of sparsely populated areas reasonable access to services available in urban communities. In spite of the low traffic volumes, the loads to which LVRs are exposed can also be very high due to the transportation needs of local activities such as forestry, farming, fishing industry, etc.

In deviation from main roads, the total thickness of the structural layers of LVRs is typically fairly small, and the roads either have only a thin bound surface layer or no surfacing at all, i.e. they are gravel roads. From the mechanistic design point of view there is a fundamental difference between low volume roads and roads with higher traffic volumes. Due to the much weaker structure of LVRs, each heavy load application brings the structure much closer to structural failure than is the case with roads built for higher traffic volumes which have a markedly stronger structure. Consequently, deterioration of road structures built for heavy traffic volumes is normally gradual due to fatigue type behaviour, while an LVR road may be severely damaged, and actually fail, as a result of a very small number of load repetitions – in the worst extreme case even under a single heavy vehicle.

This paper focusses on describing the development of a new mechanistic design approach intended to overcome the above-mentioned shortcomings to enable meaningful structural analyses also of LVRs. The work was carried out in connection with the ROADEX project of the EU-funded Northern Periphery Programme (www.roadex.org).

2 CLASSIFICATION OF RUTTING MODES

In the case of LVRs, the dominant distress mechanism in most cases is rutting, i.e. development of unevenness of the road surface in the cross-sectional direction. Visible rutting of a road surface may, however, be the result of a number of different phenomena taking place under the surface. When deciding what types of maintenance and rehabilitation measures to take, it is of utmost importance to identify the correct mechanisms behind the rut development. For that reason, a new definition for rutting modes was suggested in the ROADEX II project by Dawson and Kolisoja (2004).

According to the suggested classification of rutting modes, the development of cross-sectional unevenness of a road surface may result from four different fundamental mechanisms called Mode 0, Mode 1, Mode 2 and Mode 3 rutting:

- Mode 0: Compaction of the non-saturated aggregate materials in the structural layers of a road is called Mode 0 rutting. Especially in the case of gravel roads, this type of rutting is not very harmful because it is self-stabilising – i.e. compaction from traffic hinders further compaction.
- Mode 1: In weaker granular materials local shear strain may occur close to the wheel load. It gives rise to dilative heave immediately adjacent to the wheel track (Figure 1) where large plastic shear strains and consequent dilation take place, leading also to loosening of the base course material. This type of rutting is thus primarily a consequence of inadequate granular material shear strength in the aggregate relatively close to the pavement surface.
- Mode 2: With better aggregate quality, the pavement as a whole may rut. Ideally, this can be viewed as the subgrade deforming and the granular layer(s) deflecting bodily on it (Figure 1). The surface pattern is a broad rut with possible slight heave away from the wheel path.
- Mode 3: Rutting may also be due to surface wear of the pavement structure caused, for example, by studded tyres. This type of rutting can, however, not be considered a structural problem of the road and is therefore not discussed in any greater detail in this context.

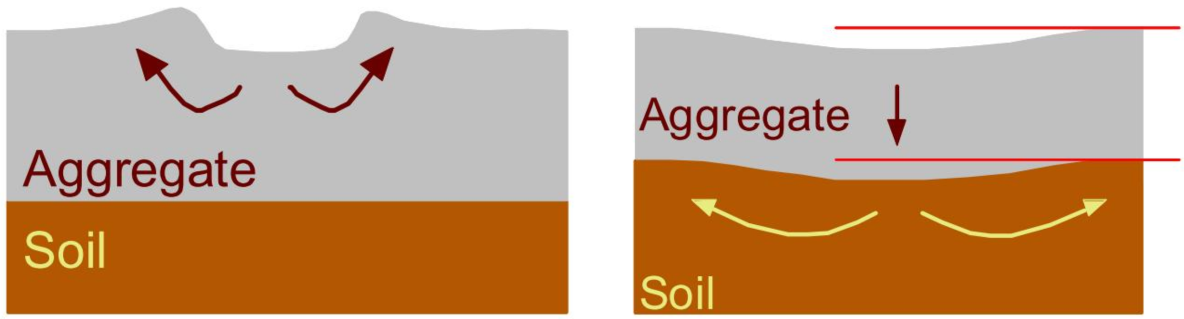

Figure1: Mode 1 rutting (left) – shear deformation within the granular layers of the pavement near to the surface; Mode 2 rutting (right) – shear deformation within the subgrade with the granular layer following the subgrade (Dawson & Kolisoja 2004).

3 ROADEX DESIGN APPROACH ON MODE 1 RUTTING

A new type of mechanistic design approach against Mode 1 rutting was developed as part of the ROADEX III project by the University of Nottingham (Dawson et al. 2008, Brito et al.

2009). The approach is based on so-called ‘proximity to failure analysis’ i.e. on analysing the shear stresses occurring at various points of a road structure exposed to a wheel load, and comparing these stresses with the shear strength of the aggregate material involved. The design approach takes into account the effects of the following variables:

- Wheel configuration: dual wheel/super single
- Tyre inflation pressure: 800 kPa/400 kPa
- Thickness of granular layer
- Aggregate stiffness / subgrade stiffness ratio
- Mechanical properties of the unbound (base course) aggregate.

In the design approach, the stresses occurring at different points of the pavement structure, as represented by the loci of maximum stress points (the blue and brown lines representing the dual and super-single tyre configurations in Figure 2, respectively), are compared to the ultimate shear strength of the unbound aggregate material as indicated by the red dotted line in the pq stress space of Figure 2.

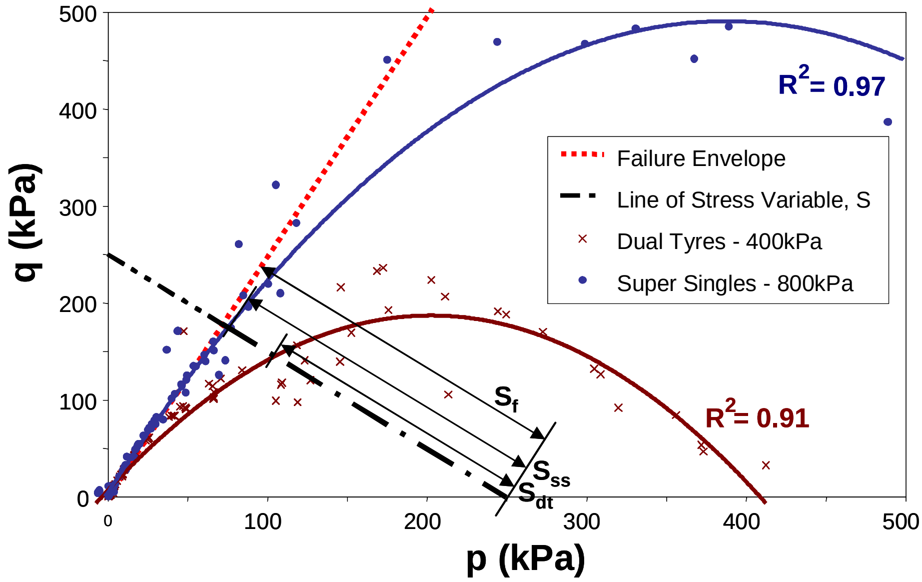

Figure2: Principle of the ‘proximity to failure approach’ (Dawson et al. 2007).

To enable comparison of the ultimate shear strength of the aggregate with the stresses that occur in the pavement structure, a somewhat arbitrary line was drawn to connect the 250 kPa point on the horizontal p-axis and the 250 kPa point on the vertical q-axis. Along this line, the distance from the horizontal axis to the failure line, S_f, is compared to the distance of the actual locus of maximum shear stresses, e.g. S_{ss} for super single and S_{dt} for dual tyres in Figure 2.

For case by case application of the design approach a set of tabulated S-values for different combinations of the variables involved are provided (Dawson at al. 2007). These values can then be compared to the value of S_f calculated based on the actual values of the shear strength parameters of the unbound aggregate. Dawson et al. (2007) suggest that this relationship should not exceed 0.90 in normal drainage conditions, and 0.75 in wet or thawing conditions.

An even more user-friendly practical application of the design approach is available in the form of a software tool on the ROADEX project website (www.roadex.org).

4 ROADEX DESIGN APPROACH ON MODE 2 RUTTING

4.1 Assessment of load distribution on the subgrade surface level

If the intention is to make a mechanistic analysis of the risk of development of Mode 2 rutting, the first logical step is to assess the amount of stresses to which the subgrade surface is exposed as a wheel load acts on the road surface. A rough estimate could be made by the so-called 1:2 distribution model, a simplified approach used in consolidation settlement analyses of geotechnical engineering. When a 50 kN wheel load acts on the top of a 0.4 m aggregate layer as shown in Figure 3, a vertical stress increase of 136 kPa can be anticipated. It should, however, be noted that the prediction totally ignores the type of material between the road surface and the subgrade level and the properties of the subgrade material itself.

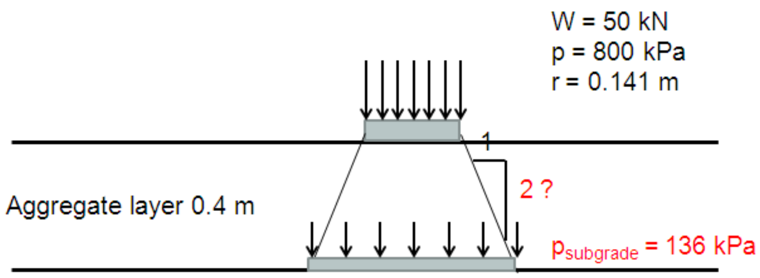

Figure 3: Assessment of vertical stress distribution based on the 1:2 distribution model.

If the type of wheel load and layer thickness shown in Figure 3 is analysed by the multi-layer linear elastic modelling approach generally applied in the stress-strain distribution analyses of pavement structures, assuming the stiffness properties of subgrade and aggregate materials of Figure 4, a maximum value of 69 kPa for the vertical stress increase directly beneath the centre of the loaded area can be expected. That value is clearly much lower than the one obtained with a 1:2 distribution model.

An even more striking observation from the latter analysis is, however, that the calculated tensile stress at the bottom of the unbound layer, directly beneath the loaded area, is as high as 165 kPa. In the case of an unbound material essentially incapable of taking tensile stresses this is of course an unrealistic situation that can certainly be assumed to have an effect also on the distribution of vertical stresses.

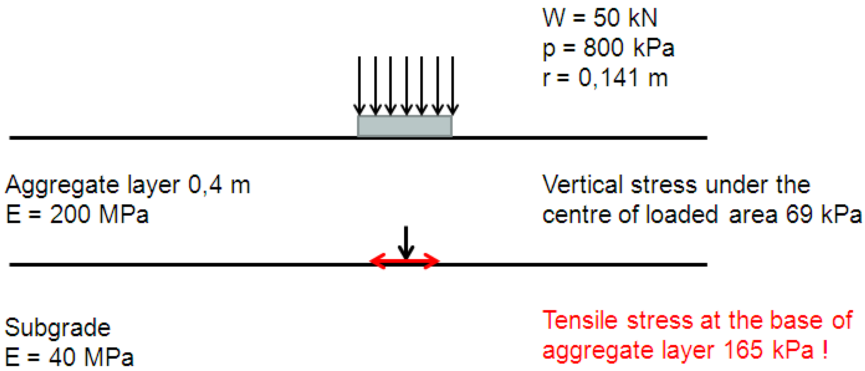

Figure 4: Example of multi-layer linear elastic modelling of a low volume road structure.

The above phenomenon is even more pronounced if the subgrade underlying the aggregate layer is softer than assumed in Figure 4. For subgrade stiffness values 20 MPa and 10 MPa, the maximum values of tensile stresses at the base of the aggregate layer are 242 kPa and 314 kPa, respectively. The corresponding predicted values of vertical stress increase, due to the wheel load directly beneath the centre of the loaded area, are 47 kPa and 31 kPa, thus predicting that the softer the subgrade material, the lower the stresses it is exposed to. The simple and obvious explanation for these results is that in the linear elastic modelling approach the layer materials are intrinsically assumed to have an unlimited capacity to resist tension, which in the case of unbound materials is, of course, a completely incorrect assumption.

Based on the above examples, it seems obvious that a more sophisticated approach for assessing stress distribution at the subgrade surface level is required. The solution is modern 3D Finite Element (FE) analysis using a material model that enables realistic simulation of the limited strength of the materials in question. In connection with this research the analysis was performed using PLAXIS FE software where the Mohr-Coulomb material model was employed in drained conditions for the aggregate layer and in undrained conditions for the subgrade soil assumed to be composed of soft clay or silt type material.

A schematic picture of the employed 3D FE model together with an example of the predicted shape of vertical stress distribution on the subgrade surface is shown in Figure 5. Correspondingly, a summary of the material parameters of the different types of aggregate and subgrade materials included in the analyses is given in Table 1. As Figure 5 indicates, the vertical stresses distribution on the subgrade surface level predicted with the 3D FE model is quite different from, but probably more plausible, than those of Figures 3 and 4.

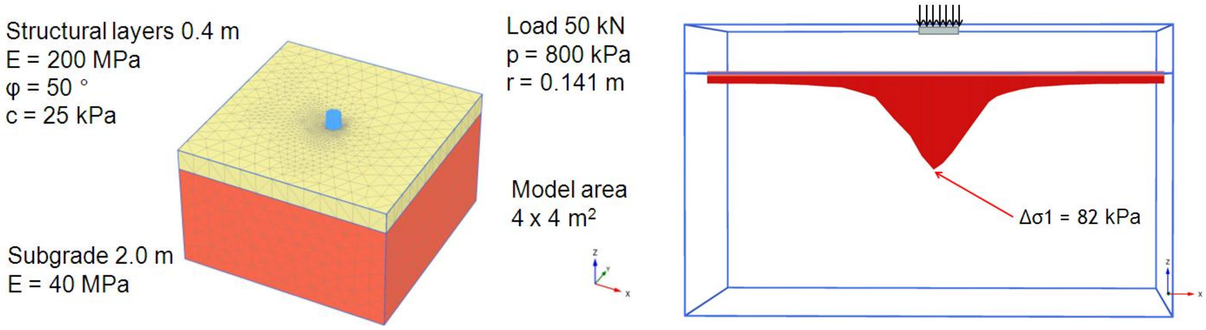

Figure 5: Distribution of vertical stresses predicted by the FE model shown on the left.

Table 1: Summary of the material parameter values employed in the FE analyses (γ_{unsat} / γ_{sat} = unsaturated / saturated unit weight, e_{init} = initial void ratio, E' = stiffness modulus, ν = Poisson's ratio, $s_{u,\,ref}$ = undrained shear strength, $s_{u,\,inc}$ = s_u increment per meter of depth, c' = apparent cohesion, φ = friction angle and ψ = dilation angle).

Subgrade quality	γ_{unsat} kN/m^3	γ_{sat} kN/m^3	e_{init}	E´ MPa	ν	$s_{u,ref}$ kPa	$s_{u,\,inc}$ kPa/m
Weak	18	18	0,3	10	0,4	10	1,5
Semi-weak	18	18	0,3	15	0,4	15	1,5
Medium	18	18	0,3	20	0,4	20	1,5

Aggregate quality	γ_{unsat} kN/m^3	γ_{sat} kN/m^3	e_{init}	E´ MPa	ν	c´ kPa	ϕ °	ψ °
Poor	21	22	0,3	150	0,3	3	40	5
Medium	21	22	0,3	150	0,3	10	45	5
Good	21	22	0,3	150	0,3	25	50	5

4.2 Basic idea of the new modelling approach

The fundamental idea behind the suggested new design approach against Mode 2 rutting is to assess the capacity of a soft subgrade soil to resist rapid accumulation of permanent deformations, essentially its ability to resist the development of a failure condition due to a low number of load repetitions, based on a normal geotechnical bearing capacity formula. The set factor of safety requirement can then be used to control the level of risk for rapid accumulation of Mode 2 type of rutting. Using the notations of Figure 6, the idea can be written in the form of Equation 1:

$$W_{\max} = \pi \cdot r_1^2 \cdot p_{\max\, surface} = \pi \cdot r_2^2 \cdot p_{\max\, subgrade} = \pi \cdot (r_1 + h \cdot LDF)^2 \cdot 1.2 \cdot 5.14 \cdot s_u \qquad \text{(Equation 1)}$$

where, W_{max} is the ultimate wheel load, r_1 is the radius of the loaded area on the road surface, $p_{max\ surface}$ is the maximum uniformly distributed vertical pressure on the road surface, r_2 is the radius of the loaded area on the subgrade surface, $p_{max\ subgrade}$ is the maximum uniformly distributed vertical pressure on the subgrade surface, h is thickness of the aggregate layer, the load distribution factor (LDF) is defined as shown in Figure 6, and s_u is undrained shear strength of the subgrade soil.

On the right side of Equation 1, the first part of expression represents the assumed loaded area at the subgrade surface level, while the latter part of expression is a direct application of a standard bearing capacity formula (e.g. Smoltczyk 2003), assuming a shape factor value of 1.2 for a circular loading area, and a bearing capacity factor of 5.14 for the shear strength of a cohesive subgrade soil in undrained conditions. The balancing effect caused by the weight of the aggregate material at the 'foundation level' indicated by the small grey arrows in Figure 6 is omitted from Equation 1 due to its relatively small overall importance in this loading condition.

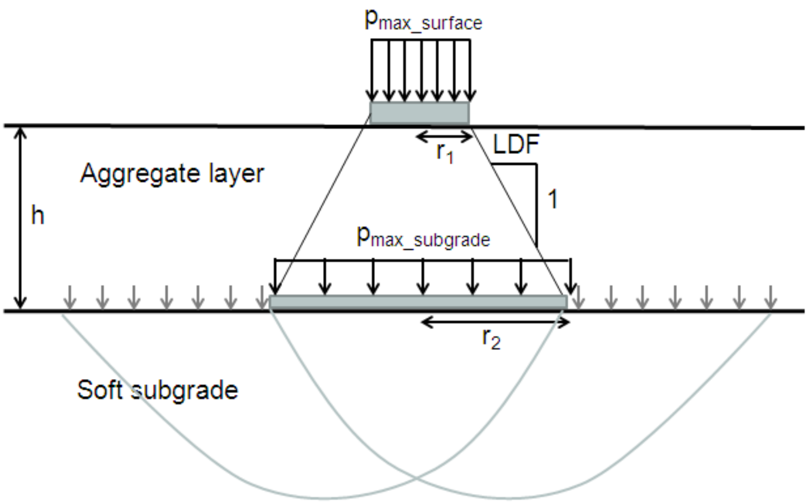

Figure 6: Basic idea of the suggested new design approach.

As the result of FE modelling in Figure 5 indicates, the vertical stress distribution at the subgrade surface level is unlikely to be rectangular in shape as sketched in Figure 6. The key idea behind the suggested new design approach is, however, to back-calculate the LDF value so that the ultimate wheel load obtained with Equation 1 corresponds to the result of respective FE simulation. In that case, it is not all that important to know the exact shape of the load distribution as long as the results concerning the ultimate value of the wheel load match.

The ultimate wheel loads must first be determined on the basis of the FE modelling results to allow performing the back-calculation procedure. In this research the definition was made somewhat arbitrarily by using the criterion of 10 mm surface deflection for the simulated load deflection curves exemplified in Figure 7. The load deflection curves of Figure 7 were obtained by increasing the (FE) simulated wheel load in increments of 10 kN and then interpolating the values between the points thus obtained.

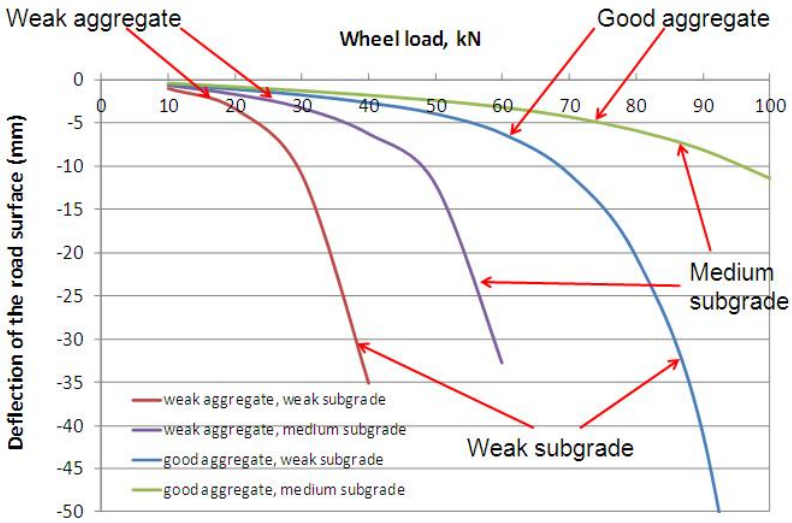

Figure 7: Examples of simulated load deflection curves obtained using the type of FE model shown in Figure 5.

4.3 Variables included in the analysis

As in the case of the Mode 1 rutting discussed in Chapter 3, it is obvious that the overall performance of the structural system shown in Figure 5 also depends on a number of variables. The focus of this research is on the following factors considered the most important ones:

- Wheel configuration: single wheel/dual wheel
- Tyre inflation pressure: 800 kPa/400 kPa
- Thickness of the aggregate layer: 0.3 m/0.4 m/0.5 m
- Effective strength parameters of the aggregate material: in practice friction angle and (apparent) cohesion (see Table 1 above)
- Undrained shear strength of subgrade soil (see Table 1 above)

The factors that can be assumed to have at least some influence on the results of analyses as those shown above include mutual ratios between the strength and stiffness properties of the aggregate and subgrade materials. At this stage it was not, however, possible to make any detailed sensitivity analysis of the effect of these factors. The variables that were given constant values in the analyses included:

- Stiffness of the aggregate layer, 150 MPa
- Stiffness of the subgrade material, 20 MPa, 15 MPa or 10 MPa depending on the undrained shear strength of the subgrade material 20 kPa, 15 kPa or 10 kPa, respectively.
- Radius of the circular contact area between the tyre and road surface, 0.141 m, except in the case of dual wheels with a tyre inflation pressure of 800 kPa when the value of 0.100 m was given for both wheels.

Straightforward analysis of the combined effects of e.g. aggregate quality and aggregate layer thickness or subgrade soil strength on the back-calculated LDF values requires simplifying the shear strength of the aggregate material to a single number. In the following such a simplification is made, somewhat arbitrarily again, based on the value of the aggregate's effective shear strength at the normal stress level of 250 kPa (Equation 2):

$$s_{aggregate} = c' + 250 \tan \varphi' \qquad \text{(Equation 2)}$$

where c' is (apparent) cohesion and φ' is friction angle of the aggregate material.

Figure 8 (left) gives the LDF values for a single wheel load arrangement as a function of aggregate shear strength and layer thickness while undrained shear strength of the subgrade soil has a constant value of 10 kPa. Correspondingly, Figure 8 (right) presents the LDF values as a function of aggregate and subgrade soil shear strength while the aggregate layer thickness has a constant value of 0.4 m.

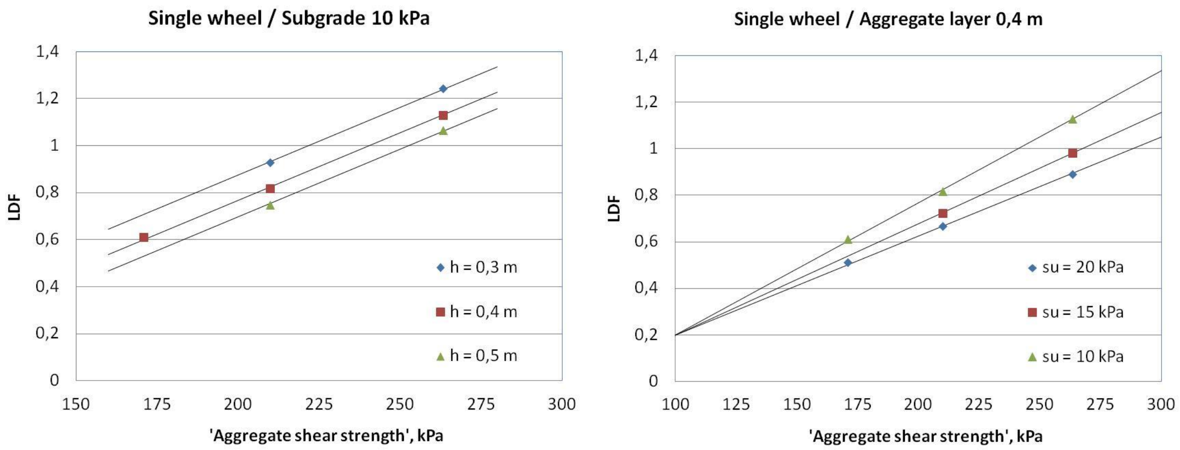

Figure 8: Load distribution factor, LDF, as a function of aggregate shear strength and aggregate layer thickness (left) and undrained shear strength of the subgrade soil (right).

Based on Figure 8, it is fairly obvious that load spreading within the aggregate layer, indicated by the LDF value (Figure 6), is the better, the higher the aggregate shear strength. Correspondingly, the LDF value is slightly higher, the softer the subgrade soil or the thinner the aggregate layer. The practical explanation is that in both of these extreme situations, the aggregate layer is forced to perform at maximum capacity to keep the structure in one piece.

The effects of other variables included in the analyses have been presented in more detail elsewhere (Kolisoja 2013). Due to space limitations, only the following is said here with respect to them:

- The respective LDF values of the dual wheel configuration are somewhat lower than those of a single wheel configuration due to the fact that the spreading of a load under one of two wheels close to each other always interferes with that of the other.
- The effect of lowering tyre inflation pressure, accomplished in practice by the use of a Central Tyre Inflation (CTI) system increasingly used e.g. in timber haulage vehicles, has hardly any effect on the risk of Mode 2 rut development if the aggregate layer thickness is 0.4 m or more.

4.4 Final outcome of the suggested new modelling approach

Equation 3 was derived by a curve fitting procedure into the LDF values corresponding to the set of lines representing the single wheel configuration in Figure 8 (right):

$$LDF_{initial} = A_i \cdot \frac{s_{aggregate} - 100}{1000} + 0.20 \quad \text{(Equation 3)}$$

where $s_{aggregate}$ is as defined in Equation 2. The value of parameter A_i is obtained from Equation 4 for a single wheel and from Equation 5 for the dual wheel configuration.

$$A_1 = 0.00785 \cdot \left(s_{u\,subgrade}\right)^2 - 0.37132 \cdot s_{u\,subgrade} + 8.62417 \quad \text{(Equation 4)}$$

$$A_2 = 0.00148 \cdot \left(s_{u\,subgrade}\right)^2 - 0.14166 \cdot s_{u\,subgrade} + 5.78148 \quad \text{(Equation 5)}$$

where $s_{u\ subgrade}$ is undrained shear strength of the subgrade soil. Due to the limited extent of analyses conducted to date, $s_{u\ subgrade}$ should be between 10 kPa and 20 kPa.

To take into account the effect of the aggregate layer thickness indicated in Figure 8 (left), the initial LDF value obtained from Equation 3 should becorrected. Based on a curve-fitting into the actual FE simulation results again, it is suggested that Equation 6 be used provided that the layer thickness h remains between 0.3 m and 0.5 m:

$$\Delta LDF = 2.0652 \cdot (h - 0.4)^2 - 0.8771 \cdot (h - 0.4) \quad \text{(Equation 6)}$$

Next, the correction increment ΔLDF is added to the value of $LDF_{initial}$ obtained from Equation 3. By then combining the preceding results with Equation 1 above, the ultimate value of wheel load W_{max} corresponding to an allowable risk level is obtained from Equations 7 and 8 for the single and dual wheel configurations, respectively:

$$W_{\max SW} = \frac{19.38}{F_s} \cdot \left(0.141 + h \cdot LDF_{SW}\right)^2 \cdot s_u \quad \text{(Equation 7)}$$

$$W_{\max DW} = 2 \cdot \frac{19.38}{F_s} \cdot \left(0.100 + h \cdot LDF_{DW}\right)^2 \cdot s_u \quad \text{(Equation 8)}$$

where LDF_{SW} and LDF_{DW} are load distribution factors determined according to the principles described above, s_u is the undrained shear strength of the subgrade soil and F_s is the (total) safety factor corresponding to the allowable risk level.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

The paper presents a new design approach for assessing the risk of Mode 2 type rutting, i.e. rapid development of excessive permanent deformations in the soft subgrade soil underlying a typical low volume road structure consisting of fairly thin layers of coarse-grained aggregate material. The developed design approach is based primarily on the idea of analysing load distribution along the aggregate layer, so as to assess the width of the distribution of the tyre contact pressure acting on the road surface at the subgrade surface level. Subsequently, a standard geotechnical bearing capacity formula is applied to determine the ultimate load carrying capacity of the subgrade soil.

In practice, the new design approach is based on back-calculating the results of 3D Finite Element modelling in a way that allows obtaining the same result in terms of ultimate load carrying capacity of the subgrade soil by a simple hand-calculation procedure as would be obtained by sophisticated 3D Finite Element modelling of the combination of loading arrangement / road structure / subgrade soil in question. Even though the new approach seems to be able to take into account the effects of key variables in a reasonably logical manner, it is important to acknowledge that the design approach is essentially based on adjusting the calculation procedure with a set of FE modelling results. Therefore, in future work it would be very important to verify the design approach by full-scale tests to be performed in-situ and based on them to make the required refinements into the calculation procedure.

More sensitivity analyses on the effects of the variables considered to be of minor importance in connection with this research are also needed. Such variables include at least the effects of aggregate stiffness, subgrade soil stiffness and the relationship between them. Moreover, the effects of wide maxi tyres and the actual shape of the contact area between the tyre and the road surface should also be studied in more detail.

REFERENCES

Brito, L. A. T., Dawson, A. and Kolisoja, P., 2009. *Analytical evaluation of unbound granular layers in regard to permanent deformation*. Proceedings of the Eighth International Conference on the Bearing Capacity of Roads, Railways and Airfields, Vol 1, pp. 187-196

Dawson, A. and Kolisoja, P., 2004. *Permanent Deformation*, Report on Task 2.1 of the ROADEX II project, 47 p. Available at: http://www.roadex.org/uploads/publications/docs-RII-EN/2_1%20Permanent%20Deformation_l.pdf

Dawson, A. R., Kolisoja, P., Vuorimies, N. and Saarenketo, T., 2007. *Design of low-volume pavements against rutting – a simplified approach*. Transportation Research Record: Journal of the Transportation Research Board, No. 1989, Vol. 1, pp. 165-172

Kolisoja, P., 2013. *Mode 2 Rutting Design Approach.* Report on Task D4 of the ROADEX IV project. *(To be published in 2013)*

Smoltczyk, U. (Ed.), 2003. *Geotechnical Engineering Handbook.* Vol. 3, Elements and Structures, p. 16. Ernst & Sohn Verlag, Berlin.