New mechanistic design approach for subgrade rutting of Low Volume Roads

Nouvelle approche de conception mécaniste de plate-forme des ornières de routes à faible volume

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ABSTRACT Until recently very few mechanistic design approaches for Low Volume Road (LVR) structures have been available, which is why they have been mostly built based on local experience and traditions. This paper describes a new mechanistic design approach intended for assessing the risk of subgrade rutting of LVRs. It is based essentially on 3D Finite Element Modelling of LVR structures, but the final results of these fairly sophisticated analyses have also been compiled into simple analytical design equations so as to make implementation of the design approach easy enough for everyday practical applications. The description of the theoretical approach is illustrated by a few application examples.

RÉSUMÉ Jusqu'à récemment, très peu de conception mécaniste approches de route faible volume (LVR) structures sont disponibles, ce qui explique pourquoi ils ont été la plupart du temps intégré basé sur l'expérience et les traditions locales. Cet article décrit une nouvelle approche de la conception mécaniste destinée à évaluer le risque de formation d'ornières plate-forme de chirurgie de l'emphysème. Il repose essentiellement sur la modélisation 3D par éléments finis des structures de LVR, mais les résultats définitifs de ces analyses assez sophistiquées ont également été compilées dans de simples équations de conception d'analyse afin de rendre la mise en œuvre de l'approche de conception assez facile pour des applications pratiques de tous les jours. La description de l'approche théorique est illustré par quelques exemples d'application.

1 INTRODUCTION

Rutting, i.e. permanent deformations that take place both in the structural layers of a road pavement and the underlying soft subgrade soil typically constitute the dominant distress mechanism of Low Volume Roads (LVRs). The situation is especially pronounced in the Northern regions of Europe and North America where roads are regularly exposed to the harmful effects of seasonal frost. Due to the limited resources available for road maintenance, the LVR structures of these sparsely populated areas have typically been built fairly weak, even though the roads are occasionally exposed to very heavy vehicle loads due to the transportation needs of local industries like forestry, aggregate production and fishing.

This paper describes a new mechanistic design approach intended for assessing the risk of subgrade rutting of LVRs developed in connection with the EU funded Northern Periphery Programme project ROADEX IV (Kolisoja 2013). The approach is essentially based on 3D Finite Element Modelling of LVR structures, but the final results of these fairly sophisticated analyses have also been compiled into simple analytical design equations so as to make implementation of the design approach easy enough for everyday practical applications.

2 PROBLEM DESCRIPTION

Mechanistic design of roads with high traffic volumes and strong structures is typically based on the inherent assumption that the structure does not approach failure condition under a single load application, but the development of distresses is rather the result of fatigue-type behaviour due to a large number of load repetitions. The analysis of the critical stresses and strains mobilized in the road structure is normally made using a multi-layer linear or non-linear elastic type of calculation model. In the case of an LVR resting on soft subgrade soil, both of these approaches are, however, highly questionable. Firstly, the structures are so weak that they can approach the failure condition under just a few load applications – during spring thaw a road may be damaged by a single pass of a too heavy vehicle. On the other hand, if the multi-layer linear (or non-linear) elastic modelling approach is applied to an LVR resting on soft subgrade soil, the stresses and strains within the structure can be predicted severely wrong as exemplified in Figure 1.

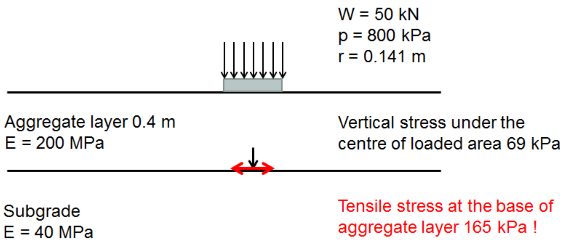

Figure 1. Prediction of stresses at the base of the aggregate layer of an LVR structure resting on soft subgrade using a multi-layer linear elastic model (W = wheel load, p = contact stress at road surface, r = radius of the circular contact area, E = stiffness).

If the stresses and strains mobilized in an LVR structure due to a single wheel loading of 50 kN are calculated using the set of input parameters shown in Figure 1, the multi-layer linear elastic modelling approach predicts that a tensile stress of more than 160 kPa develops at the base of the aggregate layer. If stiffness of the subgrade soil is lower, say 10 MPa, the predicted value of tensile stress increases well beyond 300 kPa. In the case of an unbound material unable to withstand tensional forces this is, of course, totally impossible. Consequently, the stresses and strains of any other part of this type of LVR structure cannot be predicted reliably, either.

3 FINITE ELEMENT MODELLING OF LVR STRUCTURES

A more plausible prediction of the stresses and strains mobilized in an LVR structure can be made by the Finite Element Modelling approach. In the case of single wheel loading, even an axisymmetric 2D model might be applicable, but if the loading effects of dual wheel configurations and/or multiple axles are to be analysed, a 3D model is needed. In this research the structural model of an LVR was built using the PLAXIS 3D software package.

In the FE modelling, the Mohr-Coulomb material model was employed in drained conditions for the aggregate layer and in undrained conditions for the subgrade assumed to be consisting of soft clay or silt type of soil. A schematic picture of the 3D FE model together with the predicted shape of vertical stress distribution on the subgrade surface level obtained using the indicated values of input parameters is shown in Figure 2. A more detailed description of the FE model and the related material parameters has been given elsewhere by Kolisoja et al. (2013).

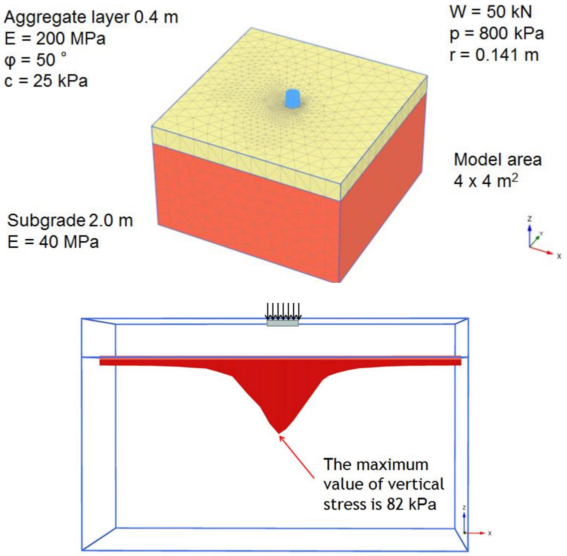

Figure 2. 3D FE model of an LVR structure resting on soft subgrade soil and the predicted vertical stress distribution on top of the subgrade (φ = friction angle, c = cohesion, the other notations are as in Figure 1).

The FE analyses performed in connection with this research project involved variation of both the material parameters used for the aggregate layer and the subgrade soil. The parameter values thus employed were selected based on earlier experience and, especially, the strength parameters of the aggregate, c and φ, drawn from an extensive series of large scale monotonous loading triaxial tests reported in more detail earlier by Kolisoja et al (2013). A summary of the respective values of key material parameters used for the subgrade soil is given in Table 1 and for the aggregate layer in Table 2.

Table 1. Key material parameters used for the subgrade soil (E' = stiffness modulus, ν = Poisson's ratio, $s_{u,\,ref}$ = undrained shear strength, $s_{u,\,inc}$ = s_u increment per meter of depth).

Subgrade quality	E' MPa	ν	$s_{u,ref}$ kPa	$s_{u,inc}$ kPa/m
Weak	10	0.4	10	1.5
Semi-weak	15	0.4	15	1.5
Medium	20	0.4	20	1.5

Table 2. Key material parameters used for the aggregate layer (E' and ν are as above, c' = apparent cohesion, φ = friction angle and ψ = dilation angle).

Aggregate quality	E' MPa	ν	c' kPa	φ °	ψ °
Poor	150	0.3	3	40	5
Medium	150	0.3	10	45	5
Good	150	0.3	25	50	5

An example of the results of the FE analyses is given in Figure 3. It shows the simulated values of surface deflection for an LVR resting on a soft subgrade soil with a structural layer thickness of 0.4 m as the wheel load acting on a circular contact area on top of the road has been increased. The obvious result based on Figure 3 is that it is not only subgrade quality that matters, but that poor quality aggregate cannot spread the load properly whereby surface deflections increase much earlier than in the case of high quality aggregate.

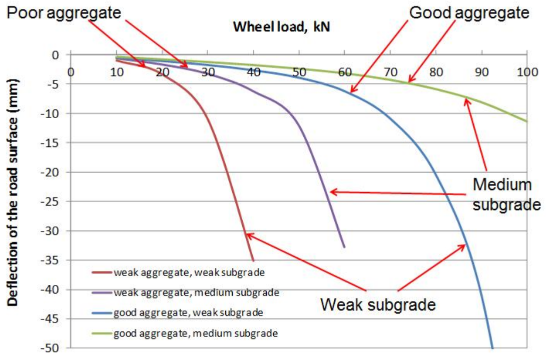

Figure 3. Simulated load deflection curves obtained using the type of FE model shown in Figure 2.

4 DERIAVATION OF THE NEW DESIGN APPROACH

4.1 Basic idea of the modelling approach

The basic idea behind the suggested design approach against subgrade 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 under a low number of load repetitions, based on a normal bearing capacity formula. The set requirement for the safety factor can then be used to control the level of risk of rapid accumulation of subgrade rutting. Using the notations of Figure 4, the basic idea can be written in the form of Equation 1:

$$\begin{aligned} W_{\max} &= \pi \cdot r_1^2 \cdot p_{\max surface} = \pi \cdot r_2^2 \cdot p_{\max subgrade} \\ &= \pi \cdot (r_1 + h \cdot LDF)^2 \cdot 1.2 \cdot 5.14 \cdot s_u \end{aligned} \qquad (1)$$

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 respective value of 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 respective value of 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 4, and s_u is undrained shear strength of the subgrade soil.

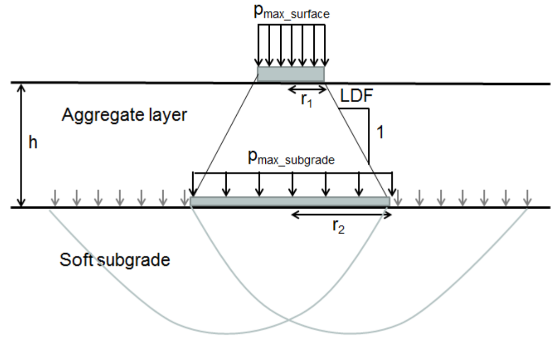

Figure 4. Basic idea of the suggested design approach against subgrade rutting.

Since the value of h is fairly small in the case of an LVR, the balancing effect of the weight of the aggregate layer indicated by the small grey arrows in Figure 4 is practically negligible. Thus, the respective term has been omitted from Equation 1.

As the results of FE modelling in Figure 2 indicate, the vertical stress distribution at the subgrade surface level is unlikely to be uniform in shape as sketched in Figure 4. 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 the respective FE simulation. Then, 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, however, first be determined on the basis of the FE modelling results to enable performance of the back-calculation procedure. In this research the definition of failure was made somewhat arbitrarily by using the 10 mm surface deflection criterion for simulated load deflection curves such as those shown in Figure 2.

4.2 Variables included into the analysis

The variables included into the performed set of FEM analyses included:

- 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
- Undrained shear strength of subgrade soil (see Table 1 above)
- Effective strength parameters of the aggregate material: in practice friction angle and (apparent) cohesion (see Table 2 above)

Stiffness values used for the subgrade soil and aggregate were as shown in Tables 1 and 2, respectively, and the radius r_1 in Equation 1 had a value of 0.141 m, except for dual wheels with a tyre inflation pressure of 800 kPa where the value was 0.100 m.

If we then assign 'aggregate shear strength' $s_{aggregate}$, somewhat arbitrarily again, as its value at the normal stress level of 250 kPa (Equation 2), the back-calculated values of Load Distribution Factor, LDF, are as exemplified in Figure 5.

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

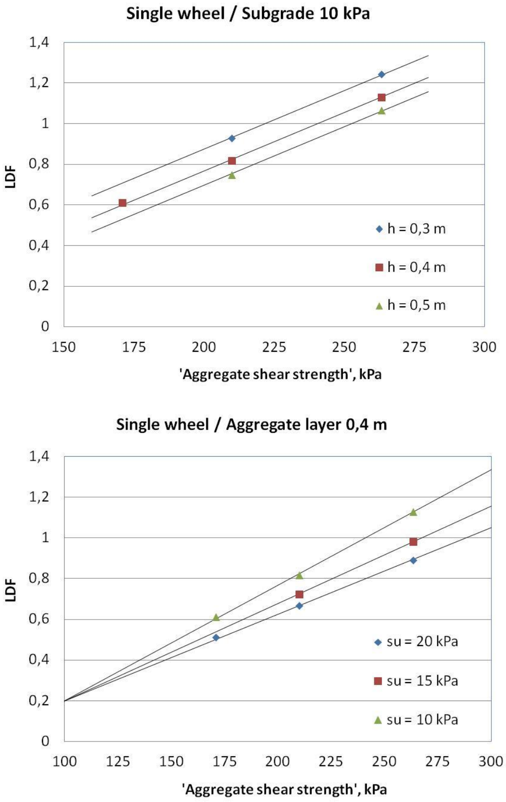

Figure 5. Load distribution factor, LDF, as a function of aggregate shear strength and aggregate layer thickness (upper) and undrained shear strength of the subgrade soil (lower).

Based on Figure 5, it is fairly obvious that load spreading within the aggregate layer, indicated by the LDF value (Figure 4), is the better, the higher is the aggregate shear strength. Correspondingly, the LDF value is slightly higher, the softer is the subgrade soil or the thinner the aggregate layer. The effects of other variables included in the analyses have been presented in more detail elsewhere (Kolisoja 2013).

4.3 *Final formulation of the modelling approach*

By performing curve fitting on the LDF values like those exemplified for an aggregate layer thickness of 0.4 m in Figure 5 (lower) we get a mathematical expression for LDF as follows:

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

where $s_{aggregate}$ is as defined in Equation 2. The values of parameter A_i representing the slope of lines shown in Figure 5 (lower) corresponding to different values of subgrade strength are again obtained based on curve fitting procedure. They can be expressed in the form of Equations 4 and 5 for single wheel and dual wheel configurations, respectively:

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

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

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 5 (upper), the initial LDF value obtained from Equation 3 should be corrected. Based on a curve-fitting on 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:

$$\Delta LDF = 2.0652 \cdot (h - 0.4)^2 - 0.8771 \cdot (h - 0.4) \qquad (6)$$

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:

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

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

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 APPLICATION EXAMPLES OF THE NEW DESIGN APPPROACH

For easy practical application of the suggested design approach, the above equations could e.g. be entered into a spreadsheet program, especially if optimisation of the design solutions is planned.

Let's consider the design case shown in Figure 6 where the assumed design parameters concerning both wheel loading and the aggregate layer/subgrade soil have been summarised. The question then is: how thick should the aggregate layer be to avoid too rapid accumulation of permanent deformations in the soft subgrade soil.

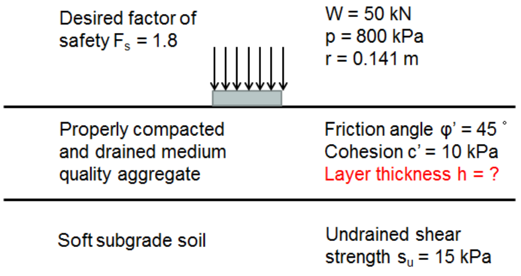

Figure 6. Input data for the design example (single wheel configuration).

At first, an initial guess concerning the required layer thickness must be made, let's make it h = 0.5 m. By substituting the input data in Equations 2 to 7 the calculation proceeds as follows:

Eq. 2: $s_{aggregate} = 260$ kPa
Eq. 3: $LDF_{initial\ SW} = 0.9713$, where
Eq. 4: $A_1 = 4.8206$
Eq. 6: $\Delta LDF = -0.0671$
$LDF_{SW} = 0.9042$
Eq. 7: $W_{max\ SW} = 56.8$ kN

Because the obtained maximum allowable value of wheel load of 56.8 kN is now higher than the design wheel load 50 kN, it would be possible to reduce the required layer thickness. In this case, after some iterations we could get a minimum layer thickness of 0.45 m.

If we then want to make a similar analysis for a dual wheel configuration, the calculation procedure is exactly the same except that instead of Equations 4 and 7 we now use Equations 5 and 8, respectively. An initial layer thickness of 0.5 m gives us now a maximum load of 76.2 kN for the dual wheel configuration. Correspondingly, the optimised layer thickness that allows applying a 100 kN axle load, i.e. 50 kN load for a pair of dual wheels, is 0.33 m.

Further, if we want to assess e.g. the effect of subgrade quality on required layer thickness, we just need to repeat the calculation procedure with the modified input values. Assuming an undrained shear strength of the subgrade of 10 kPa, the required aggregate layer thicknesses increase to 0.53 m for a single wheel configuration and 0.43 m for a dual wheel configuration. If the undrained shear strength of the subgrade soil was 20 kPa, the required minimum aggregate layer thicknesses would be 0.38 m and 0.27 m, respectively.

6 CONCLUSIONS

A new design approach for assessing the risk of subgrade 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, has been developed. The 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. Then, a standard geotechnical bearing capacity formula is applied to determine the ultimate load carrying capacity of the subgrade soil.

In practice, the suggested 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 loading arrangement/road structure/subgrade soil combination 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 to date the design approach is essentially based on adjusting the calculation procedure with a set of FE modelling results. Therefore, it is very important that in future work the design approach is verified by full-scale tests performed in-situ to allow making the required refinements to the calculation procedure.

ACKNOWLEDGEMENT

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