Application of line loads versus block loads for railway embankment stability assessment

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1 Introduction

In the Netherlands ProRail is the asset owner and manager of the rail network. For the stability assessment of existing railway embankments ProRail prescribes the use of guideline RLN00414-1 [1]. The train loads as mentioned in this guideline are based on the load models as presented in NEN-EN 15528 [2]. The ProRail guideline prescribes the use of the so-called Block Load as input for the static 2D limit equilibrium (LEM) slope stability check. Effectively, the Block Load is the surface load acting on top of the embankment (underneath the ballast bed) coming from two adjacent train bogies and averaged over a limited area underneath these bogies (Figure 1). This approach is conservative in the sense that 3D effects occurring in the slip plane are ignored. By including the 3D effects, the full train load may be averaged over the full train length if certain application conditions apply. The resulting averaged load is generally referred to as the Line Load, expressed in tons per meter, in compliance with [2]. Note however that in the context of this study the Line Load will be referenced as a surface load, i.e. the load is also spread over the width of the railway track.

Within the RESET research program, the mentioned 3D effects are quantified by means of a series of 3D finite element (FE) calculations [3, 4]. Main goal of these calculations is to determine under which conditions it is allowed to apply the Line Load instead of the Block Load.

RESET is an acronym for the collaborative research program 'Reliable Embankments for the Safe Expansion of rail Traffic', between ProRail, TU Delft and Deltares. The aim of this program is to provide ProRail with the required methods, tools and knowledge to assess the actual geotechnical stability of railroad embankments as a function of the frequency and length of trains, loads and speeds.

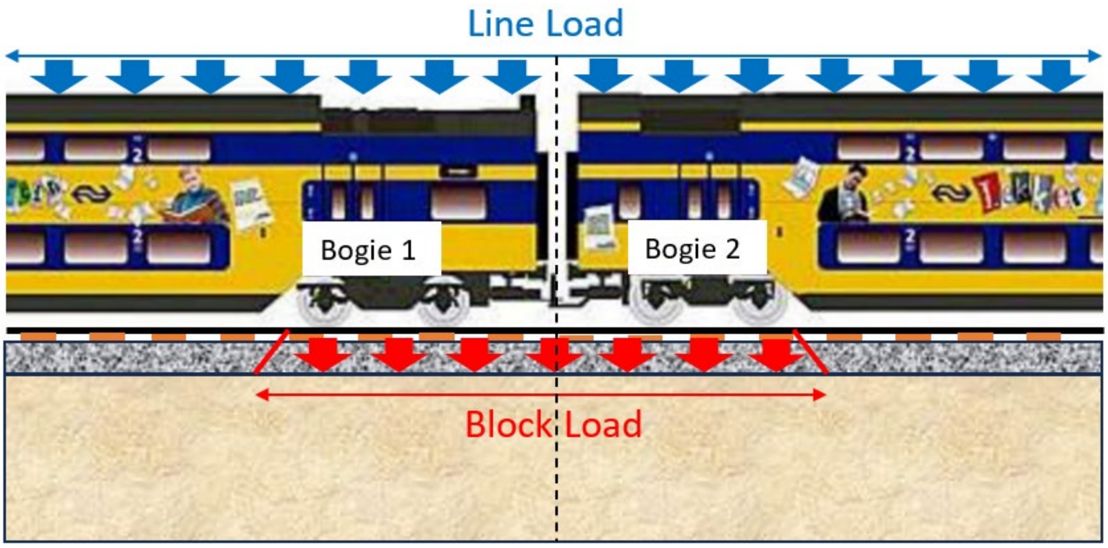

Figure 1. Illustration of the block load vs line load.

2 Finite element model set-up

To quantify the 3D effects and determine under which conditions it is allowed to apply the Line Load instead of the Block Load a variation study was undertaken with the finite element (FE) software PLAXIS 3D. The variation study is performed in an automated manner and relevant variables such as embankment height, slope angle, thickness and properties of the cohesive layer and presence and location of the ditch are varied over a realistic range, relative to a base model. In total 1620 combinations are calculated. Note that the base model consists of only one railway track.

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Variations with a base model with two railway tracks have been made leading to similar results as using one railway track.

Focus is put on the D4 train load model [1, 2] as ProRail indicates this to be a governing load in many situations for the stability assessment. For the D4 load model a Block Load value of 35 kPa is prescribed in the RLN00414. Based on the length and weight of the D4 train load model a Line Load value of 26 kPa can be determined. Both the Block Load and Line Load act over a width of 3 m, perpendicular to the slope, at the bottom side of the ballast bed. Besides the variation of relevant variables throughout the different FE models, several load situations are calculated in each individual FE model, also see Figure 3:

- The Block Load is applied over a limited part of the model width, parallel to the slope as depicted in Figure 3a. By means of use of the safety functionality in PLAXIS, the model generates a safety factor (SF) referred to as SF3D;
- Next the same surface load as the Block Load is applied, but now over the full width of the FE model, see Figure 3b. Such a model is considered to be equivalent to the 2D (LEM) model generated in practice used for the slope stability analysis. Note that the total applied load on the slope is an overestimation of the total weight of the train. This model generates a safety factor referred to as SF2D;
- Finally, the Line Load is applied over the full width of the FE model, see Figure 3c. This model generates a safety factor referred to as SF2Dline.

A relevant aspect of the FE model set-up is the use of double symmetry, allowing for an efficient FE model. Effectively only the right half of the situation in Figure 1 is modelled. See Figure 2 for an example of the 3D FE model set-up. The nodes on the vertical boundaries are normally fixed (including y_{min} and y_{max}). The nodes at the bottom of the model have full fixity simulating a strong and stiff foundation layer. The base model consists of a drained sand embankment, with varying height and sand thickness, on top of a soft undrained cohesive layer with presence of a ditch next to the embankment. The material models and parameters used for the soil layers in the base model are shown in Table 1 and 2. The groundwater table is located at 25 cm below the top of the soft cohesive layer.

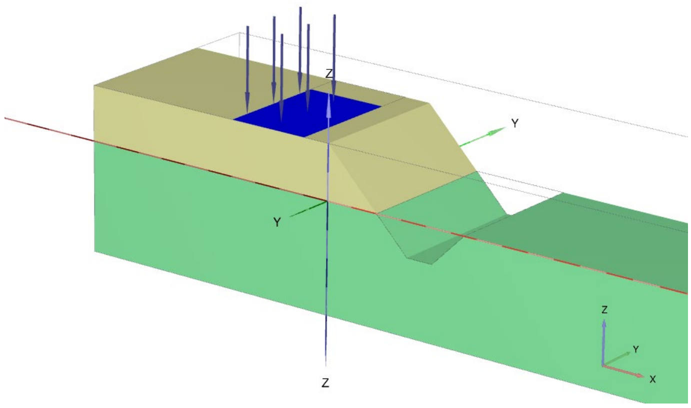
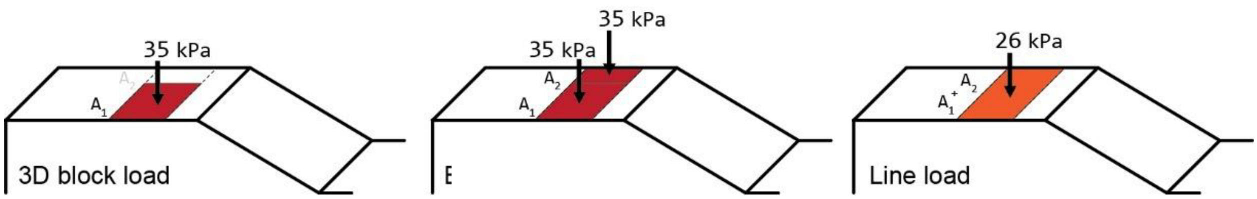


Figure 2. An example of the 3D FE model set-up with application of the Block Load.



(a) (b) (c)

Figure 3. Distinction of the three separate load situations calculated in each FE model, (a) the Block Load applied over a limited area, (b) a surface load with the same value as the Block Load over the model width, (c) the Line Load over the model width.

Table 1. Properties used for the sand embankment (base model).

Layer	Material model	γ_{unsat} / γ_{sat} [kN/m^3]	E'$_{50\_ref}$ [MPa]	E'$_{oed\_ref}$ [MPa]	E'$_{ur\_ref}$ [MPa]	m [-]	ϕ' [degr]	ψ' [degr]	c' [kPa]
Sand (drained)	Hardening Soil model	18 / 20	20	20	60	0.5	30	0	1

Table 2. Properties used for the soft cohesive layer (base model).

Layer	Material model	γ_{unsat} / γ_{sat} [kN/m^3]	G/s_u^A [-]	γ_f^C / γ_f^{DSS} / γ_f^E [%]	τ_0/s_u^A [-]	s_u^{DSS}/s_u^A [-]	s_u^P/s_u^A [-]	S [-]	m [-]
Soft, cohesive (undrained)	NGI-ADP-SHANSEP	11 / 11	500	8 / 10 / 12	0.6	0.99	0.99	0.38	0.90

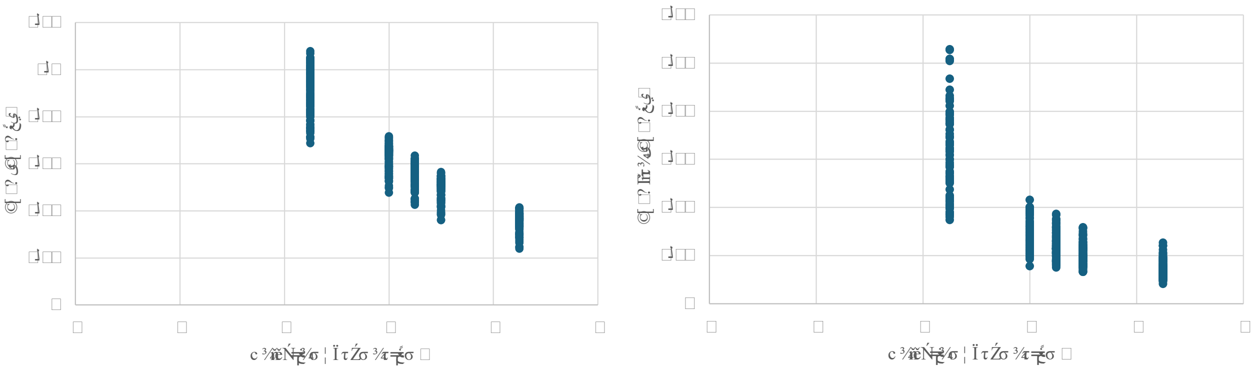
3 Finite Element model output

The resulting model outputs (i.e. safety factors) are collected in a database and are presented in two different manners (Figure 4) as follows:

a) The ratio of SF3D/SF2D is presented as a function of the height of the embankment providing insight into the increase of the stability factor as a result of the 3D effects.
b) The ratio of SF2Dline/SF3D is presented as a function of the height of the embankment. If these values are within a 2% accuracy of each other, it is thought that the Line Load may be used in practical applications. As an example: if SF3D = 1.00 and SF2Dline = 1.02 the values are considered to be the same from a practical viewpoint and a Line Load may be used.

While inspecting Figure 4 please note that by presenting ratios of safety factors the mesh sensitivity is significantly reduced. Mesh effects may play a significant role in the absolute values of the safety factors in a 3D model. However, the ratios of safety factors, extracted from the same FE model, are much less sensitive to mesh size as confirmed by several sensitivity checks. Furthermore, note that individual calculation results are presented as dots, due to overlapping of these dots results may give the impression of straight lines. Finally, note that the embankment height is defined as relative to the adjacent soil surface or when a ditch is present, relative to the bottom of the adjacent ditch.

As can be seen from Figure 4a, for a larger embankment height the influence of a train load on top of the embankment is relatively small, i.e. the stability is dominated by the weight of the embankment. As such the 3D effects are relatively small. For a smaller embankment height, the train load has a relatively large effect compared to the weight of the embankment and as such the 3D effects are relatively large. From Figure 4b it can be seen that from an embankment height of 3m or more the ratio of SF2Dline/SF3D is within a 2% accuracy.



(a) (b)

Figure 4. Presentation of model output: (a) as a function of the ratio SF3D/SF2D against embankment height and (b) as a function of the ratio SF2Dline/SF3D against embankment height.

4 Conclusions

The following proposal is made for the static 2D limit equilibrium (LEM) slope stability check in engineering practice:

- D4 Line Loads are appropriate to apply for sand embankments with a height (and sand thickness) of 3m or more, relative to the average adjacent soil surface level, in absence of a nearby ditch. In case there is a nearby ditch the height (and sand thickness) of 3m may be measured relative to the bottom level of the ditch.
- For other situations, the D4 Block Load should be used, where 3D-effects can be accounted for by multiplying the 2D LEM Factor of Safety with a model factor of 1.05.

Note that several application conditions apply with aforementioned proposal as outlined in [3].

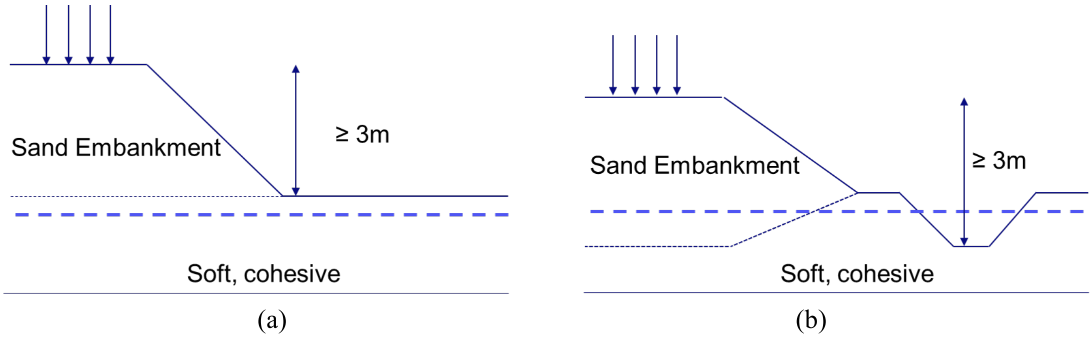


Figure 5. Proposal for when to apply a Line Load: (a) situation without a ditch and (b) situation with a ditch.

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