RAILWAY ACTIONS ON EMBANKMENTS AND RETAINING WALLS – COMPATIBILITY BETWEEN LOAD MODELS

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KEYWORDS

Railway, Axle Loads, Geotechnical Loads, Load models, 2D/3D Failure

ABSTRACT

Load models for rail traffic on bridges are specified in EN 1991-2 (2003) comprising e.g. LM 71, SW/0, and SW/2 but these are applicable for bridges and not the adjacent geotechnical structures, e.g. embankments and retaining walls. This paper discusses the background for the train load models applied in Denmark for geotechnical structures. Reference will be made to EN 1991-2, EN 15528 and the technical specifications for interoperability (TSI INF). Possible revisions to the existing load models are discussed following the idea that loading on the rails originate from axle groups and that the equivalent line loads may be derived from these groups. Load models for geotechnical structures must therefore reflect an axle load and a line load scenario, but not a combination of axle and line loads within the same model as seen in LM 71.

1. INTRODUCTION AND BACKGROUND

Railway actions on bridges are covered by EN 1991-2, [1], e.g. load model 71 (LM 71). LM 71, which is shown on Figure 1, does not represent a real train but it includes a combination of load components being critical for local and global stability of bridges. Train loads on neighbouring geotechnical structures must respect EN 1991-2 but shall be carefully established to reflect critical loading aspects for geotechnical structures. The TSI INF requirements, [2], for the European railways state that LM 71 must be used for earth work structures. This is intended to ensure a compliant railway system across Europe, but it does not provide clarity as to how to implement load models for geotechnical structures. The scope of this paper is to present and discuss the

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approach taken by Rail Net Denmark to establish compliant load models for new geotechnical structures. In addition, suggestions have been put forward to discuss requirements in [2] and the approach taken by Rail Net Denmark in their railway standard BN1-59-4, [3] representing supplementary structural and geotechnical Danish requirements to [1] and [2]. Focus for this paper is to present the origin of the load applicable for design of geotechnical structures and to discuss geotechnical aspects related to railway actions.

2. DANISH LOAD MODELS

The Danish load models for new geotechnical structures are defined by the guidelines set out in [3] from Rail Net Denmark, which offers non-contradictory complementary information to the requirements defined in [1], [2], and EN 15528, [4]. The following rules apply (cf. [3]) for the design of new embankments, new retaining walls and sheet piles:

For stability of embankments i.e. 2-dimensional calculations, single tracks must be subjected to an infinite line load 175 kN/m. Double tracks or more parallel tracks with a line load of 175 kN/m in most critical track, a line load of 110kN/m in the nearest track, and no load on other tracks.

Calculating the earth pressure on support walls and sheet pilings, including walls for frame bridges, the local increase of loads from boogie-shafts must take account of 3D-effects. Thus, for single tracks locally increased line load 250 kN/m over a 6.4 m stretch is applied and outside this stretch 135 kN/m as an infinite line load. For parallel tracks the loads model for single tracks is applied in the most critical track, combined with a line load 110 kN/m in the nearest track, and no load for other tracks.

The following goes for all line loads: a) They are distributed at the base of the sleepers (2.5 m width), b) Dynamic allowance is included and c) The loads must be used without a reduction in both drained and undrained cases.

The load models above are aligned with the guidelines in [1], where a separation between global and local structural effects is introduced and the geotechnical reflection is likely to distinguish between local failures (e.g. from concentrated axle loads i.e. a 3D case) and global failures, e.g. an average consideration of loads distributed over a length of a train (a 2D case). The proposed geotechnical distinction between local and global failures will align with the intention of [1] and aid the designer in selecting an appropriate design tool. The idea in [3] is that geotechnical load models must be simple to avoid misunderstandings, and that code requirements often can be met using rather simple means.

The basic model for vertical loads in [1] is LM 71 as illustrated on Figure 1 with four axle loads, each representing 250 kN, and with uniformly distrib-

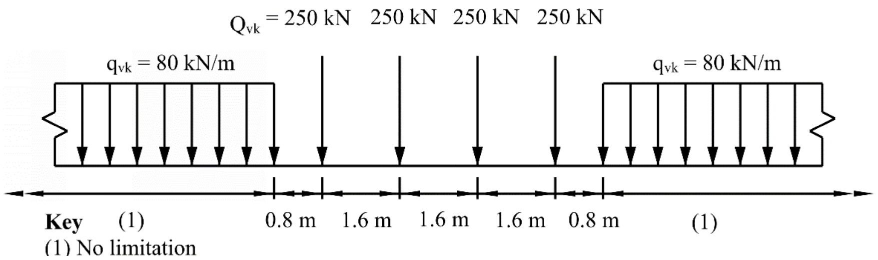

Figure 1. Load model 71 and characteristic values for vertical loads, EN 1991-2, Figure 6.1.

uted line loads outside the point loads. The point loads may reflect two closely spaced bogie axles and are intended to govern the design of <u>local</u> elements, whereas the global load effects are less influenced by these point loads. The distribution is, however, dependent on the loaded length and the size of the structure.

For 2D-analyses (plain strain) e.g. for geotechnical railway embankments, LM 71 has been interpreted based on the following principles, which laid the grounds for the loads presented by [3]: a) The 2D load model should cover the local failure (3-dimensional failure shape) associated with two closely spaced axle groups, b) a purely global failure (2-dimensional failure shape) can be covered by the infinite line load of LM 71 only, c) for loads on double tracks the failure, although considered as a global one, may start as a local failure in one track and develop into a global failure, and d) the 2D line load cannot exceed the line load of LM 71 if the loaded length exceeds 12.5 m (i.e. four point loads of 250 kN divided by 80 kN/m). This agrees with the principles of [4], i.e. corresponding to real rail traffic actions. For 2D-analyses, the load model for heavy trains, SW/2, defined by [1], is considered as an infinite line load corresponding to a global failure mode. In general, the loading presented by [3] is set out as an envelope, covering selected design cases, presented in [1], [2] and [4]. The following subsections illustrate this approach.

The equivalent line loads given in [3] for 2D analyses includes an α-value of 1.33. Compared to the point loads of LM 71, the loaded length assumed to reach the loading of 175 kN/m is 7.6 m (= 1.33 · 4 ·250 kN / 175 kN/m) compared to combined length over the axles of 6.4 m in LM 71 i.e. additional 0.6 m used for distribution of load at both ends of the axle group. Compared to LM 71, also including the line loading when distributing the point load, this load corresponds to an equivalent loaded length L = 9.6 m (175 kN/m · 9.6 m = (9.6 m – 6.4 m) · 110 kN/m + 4 · 1.33 · 250 kN). Considering the stress distribution through rails, sleepers, ballast, and blanket layer, an equivalent length larger than the 6.4 m from LM 71 is physical reasonable.

For the heaviest reference vehicles in [4] (axle loads of 330 kN, α = 1.00 and a line load of 110 kN/m) the equivalent line load of two closely spaced bogies is 157 kN/m [= 4·330 kN / (2 · 1.8 m + 2 · 1.5 m + 2 · 0.5 · 1.8 m) = 1,320 kN / 8.4 m], i.e. less than 175 kN/m adopted in [3] (α = 1.33 included). [1] defines that SW/2, amounting 150 kN/m must be checked, but with a lower partial safety factor. For single-tracked railways this combination is less critical than the load defined in [1]. For railways with multiple tracks, the SW/2 is to be applied in one track, and LM 71 in the other. As the SW/2 is a line load, this situation corresponds to a global (plane strain) failure, which is why the LM 71 approaches a 110 kN/m line load (1.33 · 80 kN/m).

Based on the discussion above, the Danish rules from [3] complies with requirements in [1], [2], and [4]. Thus, the loading of 175 kN/m envelopes a) LM 71 (156 kN/m or 119 kN/m dependent on approach), b) Heaviest reference vehicle combined with future-proofing (using α = 1.33), reaching 157 kN/m, and c) Load case SW/2 required by [1], amounting 150 kN/m.

If the LM 71 axle loads are used for local analyses to investigate 3D load effects on structures, the line load associated with the four axles is 1.33 · 4 · 250 kN / 6.4 m = 208 kN/m along 6.4 m. [3] requests to use 250 kN/m along the 6.4 m i.e. approx. 20% higher than what can be derived directly from [1]. The load model for concentrated axle loads shall be used for abutments, walls of frame bridges and wings walls, allowing load spreading of the concentrated axle load through the soil parallel and perpendicular to the track. Parallel to the track, load spreading of the line load outside the 6.4 m is limited 135 kN/m in [3].

3. ANALYSES OF LM 71 FOR GEOTECHNICAL PURPOSES

The train loads experienced by a geotechnical structure originates from the axle load which is distributed through the ballast and the blanket layers to the subgrade level. Loading on the subgrade level will thus be represented by a series of vertical surcharge loads distributed along the rails, and with each surcharge load area being defined by the footprint of the axle group (plus load spreading to subgrade level). No loading will be seen between the distributed surcharge loads. The consequence of such a load configuration has been investigated by FEM using 2D and 3D analysis of a railway embankment as illustrated on Figure 2. Load spread from base of sleeper to subgrade level has been set to 0.6 m in the analysis while a sleeper width of 2.5 m has been used.

The analysis has been limited to cover one track along a straight line, excluding nosing force for simplicity. The train load is modelled through the load q_{vk1} on Figure 2 (and then multiplied by a partial factor of 1.40) while ballast, blanket layer, sleepers and rails are represented by q_{vk2} rather than discrete soil volumes (partial factor of 1.00). The length B on Figure 2 represents half the width of the subgrade layer, and it has been set to 3.45 m and 4.25 m, which are Danish minimum rules for train speeds below and above 200 km/h, respectively.

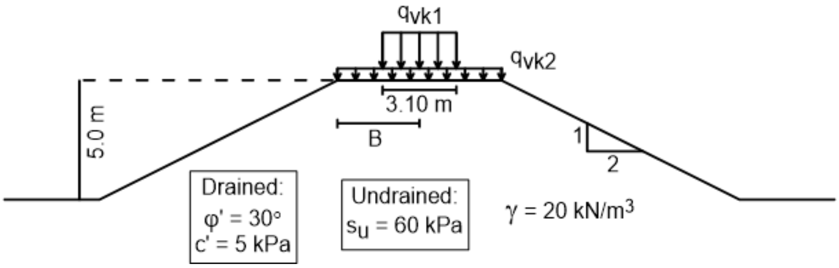

Figure 2. Embankment geometry and characteristic soil properties for a Mohr-Coulomb model. Non-associated flow with $\psi = 0°$ has been used for the drained state.

The cases investigated are defined in Table 1 and are as follows: Case a) A 2D analysis using the 80 kN/m line load from LM 71, Case b) A 3D analysis using one axle group from LM 71, Case c) A 3D analysis using 10 axle groups from LM 71, Case d) A 3D analysis using the Danish line load and Case e) A 2D analysis using the Danish line load.

Table 1. Analysed cases for assessment of load models.

Case	Environment	Design value of surcharge load (α = 1.33)
a)	Plaxis 2D	80 kN/m line load from LM 71. q_{vk1} = 80 kN/m·1.33 / (2.5 m+0.6 m) = 34 kPa
b)	Plaxis 3D	Single axle group LM 71: q_{vk1} = 4·250 kN/m·1.33 / [(6.4 m+0.6 m)·(2.5 m+0.6 m)] = 61 kPa
c)	Plaxis 3D	10 LM 71 axle groups: As case b) above. Edge-to-edge distance of 5.5 m accounting for load spread
d)	Plaxis 3D	175 kN/m line load (DK-approach with α = 1.33 included). q_{vk1} = 175 kN/m/3.1 m = 56 kPa
e)	Plaxis 2D	As case d above but conducted as a 2D analysis.

Convergence analyses were performed to ensure adequate mesh density. The safety of the system was estimated using the φ'-c-reduction method leading to a resulting safety factor ΣM_{sf}. Input values for the analysis were the design value of the train load and the characteristic values of the soil parameters. Hence ΣM_{sf} represents a back-calculated partial safety factor on tanφ' and c' (or s_u for the undrained investigation).

Figure 2 represents the 2D embankment geometry while the 3D geometry is illustrated on Figure 3, Left (axle group configuration from case c) included).

Back-calculated partial safety factors on the shear strength parameters of the soil are shown in Table 2 for drained and undrained analyses of the five cases investigated. The higher the value, the safer the structure appear. Drained results in Table 2 exceeding 1.32 (or 1.98 for undrained) reflects a safe structure in accordance with EN 1997-1 DK NA.

Table 2. Back-calculated partial safety factors on tanφ’ and c' (drained materials) and s_u (undrained materials) for the investigated cases.

	Drained materials		Undrained materials	
B [m] on figure 4	4.25	3.45	4.25	3.45
a) 2D, line load (LM 71)	1.59	1.51	2.46	2.45
b) 3D, one set of axle loads	1.80	1.71	3.05	2.99
c) 3D, 10 sets of axle loads	1.75	1.66	2.67	2.65
d) 3D, line load (Danish)	1.67	1.56	2.36	2.37
e) 2D, line load (Danish)	1.49	1.39	2.13	2.11

The conducted Plaxis analyses do not serve as a complete basis for establishing firm conclusions, but the following indications are included.

As the width of the subgrade layer increases (parameter B), the safety level increases, as expected. Comparing one LM 71 axle group [Case b)] with ten axle groups [Case c)] implies that the series of axle groups is more critical than a single axle group. In addition, the line load part of LM 71 [Case a)] implies a lower safety than the LM 71 axle group part [Case c)]. The line load part of LM 71 [Case a)] leads to a higher safety level than found when using [3] [Case e)], which can be explained by the lower line load (110 kN/m versus 175 kN/m). The friction angle of the soil causing failure for cases a) and e) are 20.0° and 21.2°, respectively, which is a small difference given the uncertainty in establishing a characteristic friction angle. The investigated embankment could have steeper slopes, which likely would cause a more severe load effect when comparing Cases a) and e).

The analyses using load models from [3] [d) and e)] yields lower safety factors compared to the LM71 axle models [b) and c)]. This may indicate that the loading set out in [3] is a safe approach, compared to the LM 71 axle groups.

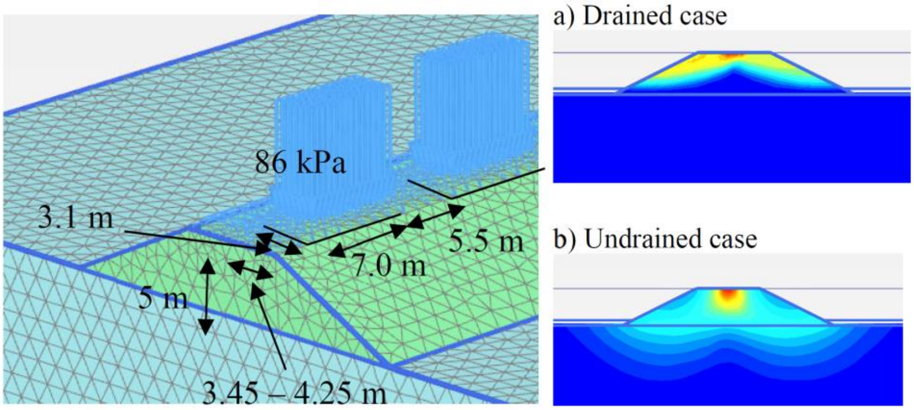

Figure 3. Left: Plaxis 3D model used for evaluation of LM 71 on geotechnical structures (86kPa = 1.4·61kPa). Green layer is embankment fill, blue layer is intact soil. Main dimensions are shown. Right: Failure mechanisms from Plaxis 3D. Cross section taken through axle no. four from the model perimeter.

Finally, line loads applied in 2D will not provide the same safety level as when used in 3D [d) versus e)]. This observation has not been studied at this stage, but the effect of the intermediate effective principal stress component should be investigated.

4. PRACTICAL DETAILS

The centrifugal forces shall be estimated in accordance with [1] where two fundamental load cases are considered if train velocities exceed 120 km/h: A slower heavy train (freight trains at 120 km/h) and a fast, lighter train (running with the allowable speed along the line). The heavy train in Denmark is modelled following [3], while the light train is modelled as the heavy train divided by α (= 1.33). Centrifugal forces will not influence a slope stability analysis provided that the radius of the curvature is sufficiently high, and a radius of 4,000 m seems to be a threshold value. [1] has not ascribed a value to the influence length for the centrifugal force, however multiple Danish railway projects have been designed using an influence length of 10 m for 2D calculations.

A clay embankment shall be investigated for drained and undrained conditions applying the centrifugal force for a curved track. The centrifugal force is linked to the mass of the train and the recommendation therefore align with the single source principle from EN 1990 [8]. Thus, one may argue that the centrifugal force should be included due to the single source principle, when investigating a drained failure in a clay embankment (short load duration indicating undrained conditions). However, disregarding the centrifugal force for drained failure would represent a load case with a parked train in the tracks.

Nosing force is caused by oscillations of train wheels due to their conical shape, and unevenness in rails and tracks, e.g. from attrition. Nosing force is a dynamic load event with a magnitude dependent on the inertia, i.e. mass and velocity. As such, the nosing force constantly changes direction and point of attack. Moreover, the magnitude of nosing will be dissipated through the ballast mat. Thus, for global failures this force is of little magnitude and could be disregarded, which is similar to [1] (Clause 6.4.5.4) stating "… abutments, foundations, retaining walls and ground pressure may be calculated without taking into account dynamic effects."

5. DISCUSSIONS / CONCLUSIONS

[1] deals with load models for bridges only, while [2] specifies that earth pressure effects shall be specified, applying LM 71. The background for the geotechnical load models from Rail Net Denmark, cf. [3] has been presented and explained in the context of [1], [2] and [4] to illustrate that load models for geotechnical structures must respect the bridge load models principles.

Based on finite element modelling, is has been shown that geotechnical load models in [3] may be on the safe side but the critical issue with a certain load model may change with the soil type, i.e. clay versus sand, and the full picture is not available at this stage. It seems that concentrated axle loads are less critical than line loads when embankments of a cohesive material are considered, and this observation somehow contradicts the use of LM 71 for geotechnical structures. Rails are loaded by axle loads and an equivalent line load may be derived from these axle loads, but line loads and axle loads acting at the same time is neither physically possible nor suitable in load models for (most) geotechnical structures. It is stressed that the conclusions offered in the present paper is valid for a selected number of cases, and that further analyses must be performed to reach firm conclusions.

The use of $\alpha > 1.0$ may be explained for bridges as train loads historically tends to increase with time and bridges are thus designed with an extra margin to absorb this, but also an increase of robustness on the main railway network in Europe. The shear strength of soil will, however, also increase with time caused by consolidation and compaction effects from repetitive axle passages, and a reduced α-value for geotechnical structures may therefore be considered.

The implementation of geotechnical load models is discussed in EN1991-2 (2023), which is yet to be implemented in Danish design practice.

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