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EFFICIENT STABILITY ASSESSMENT OF EMBANKMENTS ALONG A MAJOR RAILWAY CORRIDOR

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ABSTRACT

To further increase the appeal of rail travel in Switzerland, the Swiss Federal Railways (SBB) aims to reduce journey times on various routes. One of the strategies pursued was the ongoing use of the existing infrastructure in combination with a driving technology that enables simultaneously faster and lighter trains leading to smaller vertical loads but higher horizontal forces. This implied that the infrastructure and in particular the embankments had to be verified for the new load configurations. In this context, a comprehensive dataset covering the embankment geometry as well as information on the speed profile of the trains of an over 80 km-long railway corridor was analysed to assess the structural integrity of embankments for the revised load scenarios.

This report presents the methodology pursued to estimate the overall rehabilitation costs of the railway line for the new load configuration. This methodology includes efficient processing of the railway dataset by integrating a combination of partially automated tasks, back-calculation of subsoil parameters and targeted quality assessments.

Keywords: stability analysis, automated workflow, back calculation.

INTRODUCTION

The long-distance rail network in eastern Switzerland is planned to be enhanced by reducing passenger travel time. One potential approach explored involves the introduction of faster and lighter trains between Zurich and St. Gallen, a key corridor that connects eastern Switzerland to both regional and long-distance transportation networks. This upgrade necessitates a significant re-evaluation of the existing infrastructure, as the specific driving technique alters the load configuration. Higher train speeds affect horizontal loads, while the reduced train weight simultaneously influences both horizontal and vertical loads. Embankment sections without existing reinforcement structures are particularly sensitive to these changes.

Ideally, only targeted or partial upgrades would be necessary to ensure embankment stability for the altered load configurations. To identify critical embankment sections along this extensive railway line an efficient assessment methodology is essential. Voluminous railway line data sheets provided by the SBB, which include information on speed profiles, track curvature, and embankment conditions, serve as a basis. Additionally, cross-sectional data are available at 20-meter intervals along the entire route, providing insights into terrain geometry and track configurations. Since the project is conducted at a preliminary study level, the geotechnical parameters of the embankment subsoil are assessed through back-calculation. The applied methodology and stability analyses are presented in detail in the following sections.

METHODOLOGY

For this project at the preliminary study level, it was assumed that the current operational conditions of the trains in use comply with Swiss standards (SIA 260, SIA 261, SIA 267). On straight track sections, where centrifugal forces are negligible, lighter trains do not exceed the current loading and are therefore covered by the current conditions. Based on this premise, a filtering methodology was applied to distinguish between embankment sections that require further detailed analysis and those that do not. The entire line to be analysed has a length of 82 km and is divided into 820 sections, each 100 m long. The existing as well as the projected velocity v ($v_{current}$, and $v_{project}$) of the trains in the respective section as well as information of the curvature R is taken from the SBB datasheet for each 100 m section. Together with the existing and projected vertical loads of the trains Z, the acting centrifugal forces Q can thus be calculated for each section in both states (existing $Q_{current}$ and projected $Q_{project}$):

$$Q = \frac{Zv^2}{Rg} \text{ with } g = 9.81\text{m/s}^2 \quad (1)$$

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In the first step (step 1) of the methodology shown in the flow chart in Figure 1 a relative comparison of the centrifugal forces made it possible to identify 454 sections out of 820 that experience a higher centrifugal load in the project than in the actual state ($Q_{projected}$ / $Q_{current}$ > 1). As indicated before, only sections located in a curve according to the data sheet had to be considered.

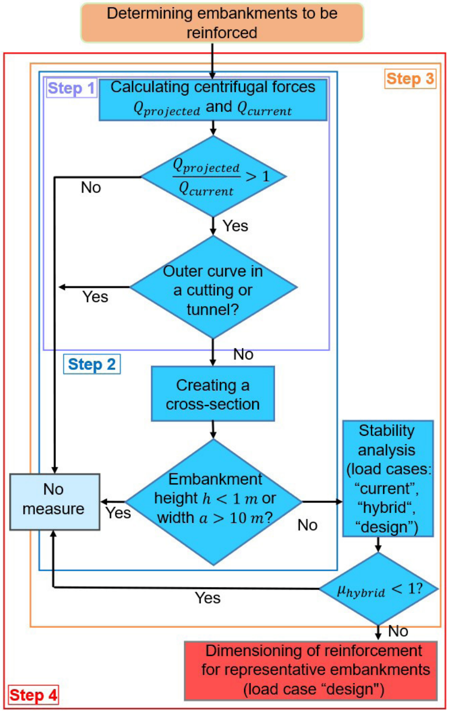

Figure 1 *Applied methodology. Degree of exploitation μ defined in Eq (2)*

From a processing point of view step 1 involves very moderate computational effort and can efficiently be done with a spreadsheet software. The 454 identified sections are first analysed geometrically (step 2) and subsequently evaluated computationally (step 3). For this purpose, they are further subdivided into cross-sections at 20-meter intervals. This process results in 2'270 cross-sections, accounting for approximately 55 % of the total railway line. For the upcoming calculations (step 3), the provided, 20 m long, cross-sections (see Figure 2) are used as a basis, in which the terrain geometry and number of tracks can be taken from. As this involves a large number of repetitive and time-consuming stability calculations, this process is automated (Meier 2021, Westermann 2020). The calculated cross-sections were subsequently verified for plausibility and by manual comparative calculations.

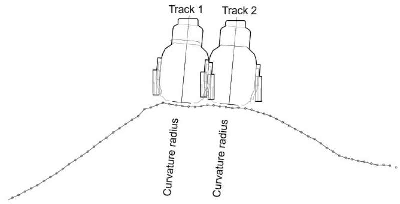

Figure 2 *Exemplary cross-section*

At step 2, an additional filtering process based on the provided cross-sections (see Figure 2) and the provided substructure table is carried out: cross-sections located within tunnels cuttings are excluded from the analysis, as they cannot be susceptible to slope instabilities. In contrast, embankment cross-sections with a height exceeding 1 meter and a width less than 10 meters (indicating a significant slope) are retained for evaluation. As a result, 23 % of all cross-sections, equivalent to approximately 18.9 km of the entire railway line, are considered in the stability assessment. For the stability calculations, three distinct load cases are considered. The first load case "current" represents the current conditions, incorporating the present train weight and speed profiles – mainly used for back-calculation of the subsoil parameters. The second load case ("design") considers the projected speed profile while maintaining the current train weight. Finally, the third load case ("hybrid") accounts for both the projected speed profile and the anticipated reduction in train weight.

In step 3, the results of the stability calculations are analysed specifically for the hybrid load case. If the degree of exploitation μ_{hybrid} (defined in the following chapter) is sufficient no measures are taken. In step 4, the remaining cross-sections that could not be identified as non-critical were assessed manually. This included an in-depth clarification of the mechanical parameters of the subsoil and, if necessary, the planning of structural reinforcement. To improve efficiency, representative embankments are defined for those remaining 3 km of the entire trainline, based on which stabilisation measures are determined.

STABILITY CALCULATIONS

Since a total amount of 2'270 cross sections were identified in step 1 for evaluation, the filtering process based on geometric characteristics of the embankments in step 2 and the stability computation in step 3 were fully automated (Meier 2021, Westermann 2020). Regarding the stability calculation, the automated procedure covered the following key aspects:

- Automated import of the DXF cross-sections and generation of a calculation model (DC-Slope input file) including adjustments to the terrain model for the requirements of the stability calculation (isolation of the embankment, simplification of the embankment geometry, etc.).

- Automatic back calculation of the characteristic subsoil parameters based on the previously generated calculation model for the current load case ("existing" load case) without considering partial safety factors (Meier 2021).
- Integration of subsoil parameters into the model using the new load configurations ("hybrid" and "design" load cases), incorporating partial safety factors to evaluate embankment stability.
- Automated evaluation of all calculations including plausibility checks

The stability calculations at step 3 are performed with the Software DC-Slope using the classic lamella method for circular slip surfaces (Krey-Bishop). In this context, the degree of exploitation μ, is defined by the ratio of destabilising moments D versus stabilising moments S (DC-Slope):

$$\mu = \frac{D}{S} = \frac{r \cdot \sum G_i \sin \vartheta_i + \sum M_S}{r \cdot \sum T_i + \sum M_R} \tag{2}$$

Where r is the radius of the circular slip surface, i is the index of the lamella and ϑ_i describes the angle of the sliding line at the lower edge of lamella i. On the destabilising side, the dead load of the lamella superposed with vertical loads G_i are considered as well as destabilising moments M_S from other loads acting on the lamella i. On the stabilising side, frictional forces on the sliding body are considered T_i as well as stabilising moments M_R. Thus, stability is achieved when the computed degree of exploitation is $\mu \leq 1$.

BACK-CALCULATION

The frictional resistance T_i is function of the strength parameters (angle of inner friction φ' and cohesion c') of the subsoil. Since these parameters are not available, a back calculation is carried out assuming that the embankment stability in its current state has a degree of exploitation of $\mu \equiv 1$ without applying partial safety factors (Meier 2021). Moreover, assuming zero cohesion $c' \equiv 0$ kN/m² shear strength of the subsoil is only defined by the angle of inner friction φ'. The subsoil is further assumed to be homogeneous with a unit weight of γ=21 kN/m³. No groundwater conditions are considered in the analysis. Under these assumptions φ' is determined through back-calculation, ensuring equilibrium in the current state, with an initial guess derived from the steepest terrain inclination. To prevent under-estimation of the stability of shallow embankments, a minimum angle of inner friction of φ'=20 ° is defined. For slope inclinations exceeding 40 °, existing stabilising components are assumed to be present in the cross-section, ensuring that no higher friction angles are assigned. Consequently, the estimated friction angles fall within the range $20° \leq \varphi \leq 40°$. If the stability analysis with these parameters result in an unstable condition (μ>1) the angle of inner friction is iteratively increased until equilibrium $\mu \approx 1$ is achieved. The back-calculated friction angle accounts for the available shear resistance, which originates from the subsoil and built-in components, if present. As no geometric modifications to the dams are planned in this specific case, this shear resistance will persist. The approach is therefore considered permissible in the presented scenario.

ANALYSIS OF THE REVISED LOADING SCENARIOS

Subsequently, a forward stability analysis using the revised loading scenarios is conducted using the back-calculated characteristic strength parameters. This analysis considers the hybrid load case (which considers partial safety factors) and employs again the Krey-Bishop method, assuming a circular sliding failure mechanism (DC-Slope). The constraint point for the sliding circles is defined as the edge of the railway tracks on the side opposite to the embankment (see Figure 3).

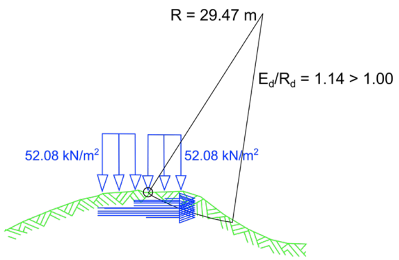

Figure 3 *Stability calculation with DC-Slope. The vertical loads describe the weight of the trains whilst the horizontal loads represent the centrifugal and lurching loads. The circle marks the constraint point*

COMPARATIVE STABILITY CALCULATIONS AND QUALITY CHECK

Since the stability calculations were fully automatised - from generating the input file with terrain geometry and applied forces to computing global slope stability - targeted comparative manual calculations and quality checks are a necessity. As part of the quality assurance process, an additional verification was conducted to ensure that cross-sections excluded in step 1, based on the provided datasheet, were justifiably omitted from further analysis. For instance, cross-sections with an indicated curvature in the datasheet (available in the 100 m segments) but not subjected to higher loads in the projected state compared to the current state were also subdivided into 20 m sections. These were then reassessed using information from the DXF file, where local curvature details were provided in text format (see Figure 2). With this critical reassessment of the available data a total of 236 additional cross-sections were identified and integrated in the stability calculations.

When it comes to the comparative calculations a total of 15 cross-sections with varying terrain profiles and stability characteristics were manually calculated by constructing their geometries into the software by hand. The iteratively back-calculated angle of inner friction φ'_{auto} from the automated algorithm was used as an input parameter in the manual stability calculations. The resulting degree of exploitation from the manual calculations μ_{manu} was then compared to the corresponding value obtained from the automatised analysis μ_{auto}. The observed deviations between the two approaches remained within the expected accuracy range of ±6 % relative to the mean value, which, according to von Matt (1976), is considered acceptable for the Krey-Bishop verification method. Consequently, the automated stability assessments were deemed reliable.

CATEGORIZATION OF EMBANKMENTS AND REINFORCEMENT MEASURES

The identified unstable embankment sections require appropriate reinforcement measures to ensure stability under the revised loads. For this purpose, the critical embankments are further categorized according to the computed degree of exploitation μ_{hybrid} under the "hybrid" load case, as well as the embankment height H into categories. Each combination of these parameters corresponds to a specific reinforcement strategy and, consequently, a designated cost. The reinforcement strategies range from subsoil investigations to structural interventions, such as the installation of steel profiles on the critical sliding side of the tracks. These profiles are designed using the "design" load case, based on a representative embankment scenario analysed beforehand. For instance, taller embankments or those with a higher degree of instability, a denser arrangement of longer steel profiles is required, directly influencing the overall reinforcement costs. By applying this categorization approach, the cost per running meter of embankment reinforcement was systematically determined.

CONCLUSION

A comprehensive stability assessment of embankments along a 82 km long railway corridor in Switzerland was conducted to evaluate their structural integrity under new load configurations. Through a combination of automated and manual stability calculations, embankment sections susceptible to instability were identified and categorized based on their computed degree of exploitation and geometrical characteristics. Due to the unavailability of geotechnical parameters for the embankment subsoil, in this early project stage an automated back-calculation approach was employed to estimate strength parameters. This method relied on a comparative analysis of existing and updated load conditions to infer soil strength properties. For each embankment category, reinforcement measures were designed based on representative embankments. This methodology enabled a cost estimation of the necessary measures, providing a basis for evaluating the feasibility of implementing the new train technology for this part of the Swiss rail network.

Ultimately, due to the high projected costs, SBB concluded that pursuing this implementation was not within reach.

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GROUND INVESTIGATION AND FIELD MONITORING