Assessment of the stability of potentially landslide-prone slopes along the federal trunk road network

Summary

Research project FE 05.0208

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1 Introduction

Gravitational mass movements can affect traffic and transport infrastructure in various ways. As part of the first phase of the BMVI expert network in the years 2016-2019 a climate impact analysis was developed in topic 1 "Adapting transport and infrastructure to climate change and extreme weather events". The impact analysis provides a methodological framework for analyzing the impairment of the transport infrastructure caused by climate change and extreme weather events. For the exposure analysis, a process-differentiated engineering-geological approach to gravitational mass movements for the federal trunk road network was developed in the research project FE89.0338/2017 (SCHIPEK & KALLMEIER 2019). This approach primarily serves to provide a nationwide overview of potentially exposed route sections. In the research project FE01.202/2019/NRB (STEFFEN & BRENDEL 2022) meteorological factors were examined and process-related threshold values, which are related to gravitational mass movements, were determined. Additionally, their possible development in the course of climate change was discussed.

The aim of this research project is to validate the existing model results in selected focus areas and to specify the risk assessment. In addition, existing models have to be improved through further development and brought into the context of climate change.

For the detailed analysis, 9 route sections in 5 study areas were defined:

1) Allgäu (Bavaria)
2) Berchtesgaden (Bavaria)
3) Moselle Valley (Rhineland-Palatinate)
4) Saxon Switzerland (Saxony)
5) Northern central low mountain range (Hesse, Lower Saxony and Thuringia)

2 Stability calculations

The geotechnical models were created using general characteristic values of the rock strata as well as literature references according to the geological descriptions. The selection of suitable calculation methods for possible slide and fall processes depends on whether the rock material represents a continuum or a discontinuum from the point of view of soil or rock mechanics. While in a discontinuum individual blocks are delimited by a number of regularly oriented discontinuities such as joint sets or bedding planes, continuum bodies exhibit a large number of different or irregular boundaries that intersect the rock mass. This applies to most soils, but also to solid rock, which, for example, has been affected by tectonic processes. Also scale plays an important role: while in the case of a small embankment or a berm, wide-ranging interfaces form individual discrete rock bodies, the number of discontinuities in a slope with large height can be so high that the rock mass can be regarded as a continuum even with large spacing between the fissures. Slides can occur both in the discontinuum and in the continuum, with sliding occurring either along predetermined sliding surfaces, e.g. bedding planes, or with the formation of new curved surfaces in the material.

The stability of potentially landslide-prone slopes of the selected profile sections was examined in conceptual models using the following methods:

- **Kinematic analysis:** Potential failure mechanisms and slide body geometries in slopes in solid rocks can be identified.
- **Limit equilibrium methods (LEM):** Calculation of stability for individual sliding bodies. Important to distinct between methods in soil and solid rock mass.
- **Stability calculation using a numerical model:** In comparison to the classical methods, calculations with numerical methods (so-called FEM - Finite Elements Modeling) are comparatively rare in civil construction practice. An essential difference is that a potential critical slip surface is formed automatically in the model according to the rock parameters and is not bound to given boundary surfaces or geometries (separation surfaces or curved paths). This is a great advantage, especially in complex geologies. A further advantage of numerical models is the the possibility to

model the subsoil and the morphology very realistically, which enables the depiction of complex geometries and additionally allows the integration of structural-geological parameters like fracture sets and faults.

3 Specification and further development of the disposition models

3.1 Basic options for specification

According to the current state of knowledge and the available data, a fundamental improvement of the mass movement maps and models can be achieved in particular by

a) using higher-resolution digital elevation models,
b) using larger-scale geologic maps and landscape models and
c) the use of alternative algorithms.

For demonstration purposes, the calculation of the indication classes for the general mass movement approach (approach 1A) was carried out on a slope along the B49. Compared to the existing model from 2019, high-resolution data in the form of a DEM5 (instead of DEM20) and geological maps on a scale of 1:25,000 to 1:50,000 (instead of 1:200,000) were used.

Due to the higher resolution gridded data, alluvial fans and in particular smaller channel were defined more clearly. In addtion, the more detailed geological data led to a reduction in the deviations and implausibilities caused by imprecise geometries. The use of landscape models with higher scales and alternative, modern algorithms are assumed to have an increasing effect of the model quality as well. According to these results, the use of datasets with higher resolutions is generally recommended.

3.2 Improvement of existing models

The further development of the existing approaches

a) general mass movements (approach 1A),
b) flow processes (approach 1B) and
c) fall processes (approach 1C)

was based on the digital elevation model with a cell size of 5 m. However, a substitution of the geological maps and landscape models from the model in 2019 could not be achieved due to the lack of available data sets with higher scales. Especially for approach 1A and 1B, the underlying calculation of the flow accumulation parameter was realized by the application of an up-to-date algorithm, which is able to describe the flow paths more realistically. Furthermore, calculations were carried out for the entire federal territory instead of the previous 1,000 m wide buffer area on both sides around the federal trunk road network, which opens up new application szenarios (e.g. route planning). With regard to approach 1C, scaling to the entire area of the Federal Republic was not possible due to methodological reasons.

The existing methodology (SCHIPEK & KALLMEIER 2019) was used for general mass movements and fall processes. For approach 1B (flow processes), the methodology was completely revised. It now aims to identify flow paths that can potentially pose a risk to people and infrastructure in case of heavy rainfall and storm events. This essentially includes all flow processes associated with erosion channels, in particular mudslides and mountain streams.

All evaluations related to the federal trunk road network were based on the current NEMO network (version number 2015_20191031) instead of the BISStra network (model from 2019). For all three approaches, the regions with areas in higher indicator classes are primarily in the low and high mountain ranges, especially in the Black Forest and in the northern Alps.

For approach 1A, there are 374 sections in direct contact with the designated potential hazard areas (29.5 km) from indication class strong, 1,946 in the range between 0 m and 50 m, 1,113 between 50 m and 100 m and 2,265 sections in the contact zone between 100 m and 200 m. In Approach 1B, there are moderately 1,337 sections with direct contact, 1,031 sections within 50 m, 522 within 100 m and 894 with extensions up to 200 m, starting from the indication class. With regard to Approach 1C, there are two very short sections from the indication class strong in direct contact with the road network (13 m). The small number and length is caused by methodological reasons. In the zone between 0 m and 50 m 3,318 sections, between 50 m and 100 m 1,613 sections and in the range between 100 m and 200 m 2,726 road sections were counted.

4 Impact scenarios

4.1 Stability calculations

Conditions that can generally reduce the stability of slopes in solid rock are essentially structural and often geometric in nature. Climatic changes have no influence on the original formation of these conditions, but their existence can partially favor changes in stability through climatic processes and also the characteristics of these conditions is changed by climatic processes in some cases. The factor of the formation of thick weathering or loosening zones mentioned in KUMERICS et al. (2012) can be directly linked to climatic conditions. In addition to weathering and rock disintegration, the presence of water and the water level is of particular importance as another major factor in the occurrence of landslides and falls. As a result of climatic influences and their possible future changes, there can be corresponding changes in pressures and stresses and material changes. Primary consequences are a reduction in shear strength, reduction or loss of cohesion, and a reduction in rock strength. Various scenarios regarding the effects of weathering (low and high thickness of the weathering zone) and changing hydrological situations (higher groundwater levels and the associated change in water pressure) were calculated on basic models of selected terrain profiles.

4.2 Climate development and disposition models

The results obtained from the project FE 01.0202/2019 NRB (STEFFEN & BRENDEL 2022) are essentially used to create the impact scenarios regarding the change in climatic conditions and their possible effect on the disposition models. Possible developments in context to conditions for gravitational mass movements were derived for the periods 2030-2061 (near future) and 2071-2100 (distant future). Assessment was realized by the use ot the obtained change signales (delta), which represent the potential change in the frequencies or the occurrence of the meteorologic parameters compared to the reference period (1971-2000). Regarding landslide processes (representative for approach 1A), a combination of the parameters precipitation duration and quantity was used, which requires a prior derivation of meterological threshold values for landslide processes. Additionally, a threshold-independed method was applied, which basically incorporates the trend of precipitation events and extracts the most intensive precipitation parts within a single event. Results were represented as precipitation duration-intensity classes, which are based on the warning levels defined by the German Weather Service for heavy and continuous precipitation events for 24 hours (https://www.dwd.de/DE/wetter/warnings_aktuell/criteria/warncriteria.html). This approach is particularly suitable for flow processes in a broader sense.

The results of the comparison of the road sections potentially affected by gravitational mass movements with the exploratory future scenarios for sliding processes show a comparatively small increase of up to a factor of 2 compared to the reference data (approx. 49% in the near and approx. 82% in the distant future scenario). However, for the Alpine region, no significant changes compared to the reference data could be determined. With regard to the comparison of the possible climatic development without reference to a threshold value (representative for approach 1B) and depending on the considered intensity classes, differences to approach 1A are apparent. With regard to the future scenarios, a general increase in the change signal could be observed from the near to distant future. In the class below 30 mm/d, 100% of the road sections are not affected by change. Between 30 - 50 mm/d, 60 - 70% of the trunk road network is located in areas up to delta 2 and about 18 - 30% up to delta 5 (near/distant future, respectively). This value is also exceeded in smaller districts (Eifel, Saar-Nahe-Bergland). Between 50 - 80 mm/d, data for the near future scenario generally show a decrease (approx. 67%), values up to delta 5 could only be observed in the Black Forest and the Alpine region. In the distant future, the fraction without change decreases to less than 30%, but increases up to delta 2 with about 55%. Road sections between delta 2 - 5 are located in the Black Forest, Harz and in the Alps. For the highest precipitation classification from 80 mm/d, an improvement in the situation is indicated in both future scenarios (approx. 95%). Only about 5% of the road sections are located in within ares up to delta 2 (Chiemgau Alps).

5 Conclusions and Outlook

5.1 Stability calculations

The created models and calculations provide an initial assessment of the stability of selected slope profiles. For this purpose, structural data from the outcrops, which were decisive for the kinematic analysis of possible failure blocks in the rock mass, as well as geological sections, were taken into account. For these sections, geotechnical parameters were researched from literature and applied to further calculations and model parameterization. A limitation for the modelling/calculations was the insufficient quantitative information about hydrogeological conditions for the individual sections, e.g. the current groundwater level in the rock mass. For this reason, as far as possible, general assumptions had to be made based on the layer structure or punctual information, or alternatively dry rock had to be calculated.

For a precise geotechnical evaluation in the engineering sense, the detailed consideration should additionally be based on specific local parameters, determined for the respective slope. Detailed data and investigations on the geological layer structure on and inside the slope as well as their physical and geomechanical properties are unfortunately not available. The created models feature therefore, due to the uncertainties of the input parameters, a more basic configuration with limited accuracy. It is therefore not regarded a stability assessment in the sense of an engineering design or implementation planning of specific slopes or slope areas from an engineering point of view. To reduce uncertainties for the assessment of stability, additional local investigations of the subsoil would be required (including detailed engineering geological documentation, sample analyses and topographical surveys). In addition to further information such as drillings, it would also be necessary to determine the characteristic soil and rock parameters based on sampling and geotechnical analysis in the laboratory. However, some laboratory test parameters, such as the friction properties of rock discontinuities in embankments can only ever be an approximation of reality due to the difference in scales. The most reliable information about the actual properties of the rock layers, in particular the large-scale properties of rock or soil, can best be determined by back analyses from failure cases. For this purpose, it would make sense in future to analyze individual recent events in detail, including necessary field and laboratory investigations, and possibly creating additional, smaller-scale detailed models/calculations.

In the stability investigations carried out in the project, the focus was set to consider the influence of changes in the characteristic soil and rock parameters and e.g. the groundwater and fissure water as a result of climatic changes. This was examined in the models through corresponding parameter variations.

5.2 Refinement, model recalculation and future scenarios

For the refinement and improvement of the models and finally the indicator maps, the example of a road section in the Moselle valley was used to impressively demonstrate the influence of data with a higher spatial resolution (e.g. DEM5). One major effect is, that areas, which were not obtained in the previous models (cell size of 20 m), can now be indicated on the indicator maps. However, a potentially negative aspect is that a higher resolution can lead to an increase in smaller areas in high indication classes, which can only be counteracted by some post-processing, e.g. through smoothing and generalization, of the resultant maps. Furthermore, in combination with an up-to-date algorithm, the discharge paths can be determined more precisely. Especially for flow processes, this opened up the possibility for the re-development of the methodology of approach 1B from scratch. However, a further decrease in the grid cell size is not recommended in general and may only be necessary for more special applications, such as the most accurate modeling of debris flows (including flow heights, etc.). Using the general mass movements approach as an example, the greatest advances were achieved by substituting the general geological map (1:200,000) with more detailed geological maps (1:25,000/1:50,000).

The nationwide creation of indicator maps for approach 1A and 1B for the entire federal territory enables new fields of application and can be used, for example, for planning new infrastructure. Since the identification of potential hazard zones is not limited to the federal trunk road network, other areas (e.g. rail- or waterways) may benefit as well. Moreover, upcoming changes of the fedral trunk road network are now much easier to update than before.

By linking the approaches 1A and 1B with the predicted climate change signals (STEFFEN & BRENDEL 2022), potential effects on the federal trunk road network could be estimated. Based on these results, it can generally be assumed, that there will be an increase in heavy precipitation events in the future and thus a greater potential for damage. This may affect both low and high mountain range regions. Especially in districts with large and branched channel systems, the predicted changes may have a grater impact than in other regions. However, an estimate, e.g. what damage can occur in the case of corresponding precipitation events, cannot be given due to the lack of comparative data.

Literature

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