Efficient risk assessment of Norwegian railways combining GIS and field studies

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ABSTRACT

A GIS-based methodology for regional scale assessment of hazard and risk along railway corridors has been developed at NGI for the Norwegian National Rail Administration.
Field investigation of hundreds of kilometres of railway is time-consuming and thus expensive to conduct. An assessment of risk along railway corridors is accomplished through substantial use of Geographical Information System (GIS), combining detailed Digital Elevation Models (DEM) and relevant railway data. The mapping method use advanced GIS analyses to identify potential high-hazard areas to closer inspect in field.
A relative quantification of hazard and consequence level is carried out for the complete stretch of railway and combined to identify low, medium and high-risk areas. The results are presented in a series of detailed maps, showing the decision-makers where further investigations and mitigation measures are most needed.
The GIS-based methodology is a time- and cost- efficient way to conduct continuous assessment of railway corridors, allowing fieldwork to be focused on inspection and evaluation of problem areas.

KEYWORDS

GIS; risk assessment; hazard mapping; railway; Norway

INTRODUCTION

Regional scale risk assessments along railway corridors using conventional mapping methods is time-consuming and thus expensive to conduct. Inspection of tens to hundreds of kilometres, obstructed by train traffic and often steep and densely vegetated terrain, make hazard assessment in the field challenging.

This paper presents a new time- and cost-effective methodology for landslide hazard and risk assessment along railway corridors at a regional scale. The methodology combines advanced analyses using Geographical Information System (GIS) with field studies. The hazards included in this study are soil slides, embankment failure caused by insufficient drainage capacity and slope failures caused by river erosion.

The presented methodology is developed by NGI through risk mapping of a total of 935 km of railway (nearly 23 % of all railway lines in Norway) for the Norwegian National Rail Administration. The purpose of the methodology is to provide a screening tool at the regional scale for problems involving linear infrastructures, to identify potential high-risk areas for detailed field investigations and future mitigation measures.

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METHODS

The methodology applies GIS for estimating the natural hazard, consequence and risk level along the railway line, with the following aims:

- Initial assessments to identify potential high-risk areas for soil slides, embankment failures and river erosion to be closer inspected in field
- Classification of low and medium risk areas not to be inspected in field
- Calculation of severity of consequence in case of a derailment along the railway corridor
- Combining hazard assessment (as calculated using GIS or evaluated in field) and calculated consequence for a continuous risk assessment along the railway line
- Present the results by producing risk maps for every kilometre of the mapped railway line

The method combines a number of relevant information in order to perform an integrated analysis in GIS. The input data to the analyses are listed below. The availability and quality of these data will affect the results.

- Digital elevation model (DEM)
- Metered railway line
- National landslide inventory
- Culvert database with information on the drainage system
- Quaternary geology maps
- Rivers, streams and lakes
- Existing river embankments
- Train speed limits
- Roads, train stations, crossings and bridges

A high resolution DEM is of key importance, as the main purpose of the GIS-analyses is to analyse the terrain along the railway. The DEM is used for calculating distances, slope angles, slope directions, embankment- and slope-heights, and drainage paths for water and watershed areas. LiDAR data are preferred, but also elevation contours with 1 m interval are acceptable for producing a high resolution DEM of 1 or 2 m grid size. The railway line is divided into segments of 10 m unit lengths for analysis purposes.

HAZARD ANALYSIS USING GIS

The hazard analyses are performed to produce relative classifications of hazard level to identify potential high-hazard areas. Different parameters believed to be critical for each of the hazard types are analysed through GIS. In the analyses each railway segment receives a hazard score between 0 and 1 for each hazard type, where 0 represents no hazard and 1 represents a high hazard level. The analyses for each hazard type are presented below.

SOIL SLIDE AGAINST RAILWAY

Soil slides in Norway are commonly triggered in slopes varying between 25° and 40°, depending on soil type. Exposed slopes are analysed in the soil slide hazard assessment using the following parameters:

- The average slope angle within the exposed slope, H_soil1
- Slope fall direction relative to railway, H_soil2
- Soil type, H_soil3
- Area of exposed slope, H_soil4

GIS is used to identify all slopes with a slope angle between 25° and 40° and fall direction towards the railway, within 30 m to each side of the railway centre line (Figure 1). The analysis verifies that the slopes are soil slopes, by checking against quaternary geology maps, and ensures that the slope is of a significant extent.

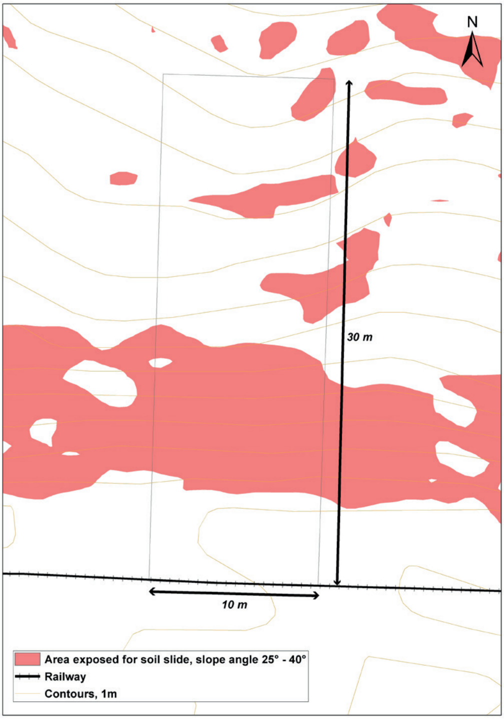

Figure 1: Soil slide hazard analysis using GIS: The terrain 30 m to each side of the railway is analysed to calculate average slope angle, fall direction and slope area.

For each parameter a score between 0 and 1 is given according to predefined classes, and they together provide the soil slide hazard score according to Formula 1

$$Soil\ slide\ hazard\ score = \ H\_soil_1\ x\ H\_soil_2\ x\ H\_soil_3\ x\ H\_soil_4$$

Formula 1: Calculation of final hazard score for soil slide towards railway

The soil slide hazard score is calculated for both sides of the railway, and the railway segment receives the highest of the two scores.

INSUFFICIENT DRAINAGE CAPACITY CAUSING EMBANKMENT FAILURES

Embankment failures along Norwegian railways are most often related to poor drainage and insufficient culvert capacity. An assessment of culverts along the railway is therefore conducted, by analysing the following parameters using GIS:

- Expected discharge HQ_{50}, H_drain1
- Culvert capacity, H_drain2
- Upstream slope angle, H_drain3

The expected discharge (H_drain1) is analysed by generating a hydrological correct DEM, and estimating the catchment area for all rivers and streams crossing the railway using the GIS-tool flow accumulation. The potential volume of discharge is then found by using a regression formula combining 50-years discharge and the associated catchment area.
Each culvert is given the greatest calculated discharge within a radius of 30 m of the culvert. The expected discharge found for each culvert is then related to the culvert capacity (H_drain2), which is calculated in m^3/s from the given culvert dimensions based on capacity charts assuming inlet control. Possible blockage of the culvert is not accounted for.

The upstream slope angle (H_drain3) is used to express the sediment transport capacity. Sediment transport towards the culvert is associated with a higher probability of insufficient capacity. The upstream slope angle is found for every culvert by calculating the average slope of the upstream waterway within the 10x30 m buffer. Slopes greater than 12° receives the highest score of 1.

The drainage capacity hazard score for all culverts are calculated as shown in Formula 2:

$$Drainage\ capacity\ hazard\ score = \frac{H\_drain_1}{H\_drain_2}\ x\ H\_drain_3$$

Formula 2: Calculation of final hazard score for embankment failures caused by insufficient drainage capacityy

The relationship between the given culvert capacity and the estimated potential discharge will express whether the culvert capacity is sufficient. Values higher than 1 is set equal to 1, and implies that the culvert capacity is insufficient.

SLOPE FAILURES CAUSED BY RIVER EROSION

The critical parameters with respect to river erosion and associated slope failures included in the GIS-analyses are:

- Distance between toe of railway embankment and river, H_erosion1
- Height difference between toe of railway embankment and river, H_eroison2

The first step is to locate the toe of the railway embankment and find the elevation using terrain analyses in GIS. This information is used for finding the distance and height difference between the toe of the embankment and the river. A distance of 30 m or more, or a height difference of 4 m or more, is regarded as a neglectable hazard level. Whereas a distance of 15 m or less, and a height difference of 2 m or less, result in the highest hazard level. The values in between will result in an intermediate hazard value.

The parameters are multiplied as shown in Formula 3, giving every railway segment a hazard score for slope failures caused by river erosion. The hazard score is compared to a national dataset with existing riverbank-stabilisation measures

$$Erosion\ hazard\ score = \ H\_erosion_1\ x\ H\_erosion_2$$

Formula 3: Calculation of final hazard score for slope failures caused by river erosion

CONSEQUENCE ANALYSIS USING GIS

For a continuous assessment for severity of consequence in the case of a derailment, a fully GIS-based methodology is applied. The consequence methodology is based on a methodology developed by Sweco (Sweco, 2012). This method was developed for risk assessments of rock cuts along the railway, based on traditional registration in the field. It was thus not well suited for regional scale risk mapping of several geohazards.

After experiences gained in the first few years with these projects, NGI modified the existing consequence methodology to be fully based on GIS-analyses and with new classifications of the parameters. Three parameters are included in the consequence analyses and explained in more detail in the next paragraphs.

ACCESSIBILITY FOR RESCUE

The accessibility for rescue (C_access) is calculated by first finding the distance to the nearest railway station, level crossing and platform for every railway segment. Secondly, the accessibility from the nearest road is calculated using a "cost-analysis" in GIS. In this analysis, distance, slope and barriers, such as rivers and cliffs, are taken into account. The results of the cost-analysis are evaluated in order to choose suitable limits for defining accessibility into the three categories easy, intermediate and difficult (figure 2).

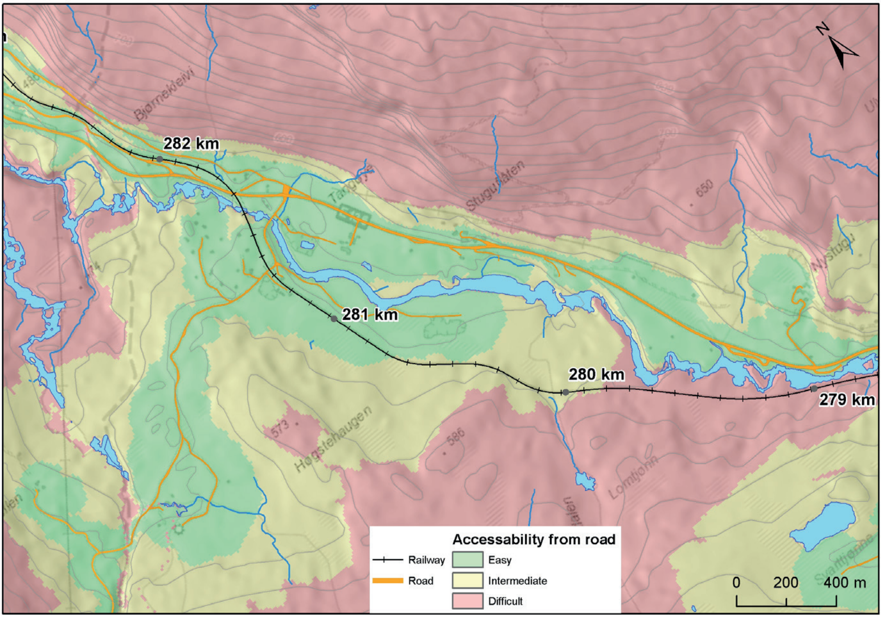

Figure 2: Example of cost-analysis in GIS, used to define accessibility from road into “easy”, “intermediate” and difficult”. The green colour represents “easy access” to the railway, and surrounds the road in different width, depending on terrain slope and natural barriers.

At stations, level crossings and platforms, it is assumed that rescue vehicles can access the railway track fast and easily. A short distance to these locations is thus regarded as a better alternative than reaching the track from a nearby road. The calculated distance is combined with the accessibility from road to express the Accessibility for rescue. The parameter is divided into seven classes with scores ranging from 1 to 8.

TERRAIN AT PLACE OF DERAILMENT

The shape of the terrain (C_terrain) within 30 m to each side of the railway is calculated using GIS through analyses of slope height, slope fall direction and distance to body of water. The higher the slope, the higher consequence score is achieved. If the slope ends in a body of water, the score is increased. If there is no slope (the railway goes through a two-sided cutting), the lowest score is achieved. The parameter is classified into six different classes with the associated scores ranging between 1 and 12.

IMPACT SPEED

Potential impact speed (C_speed) is calculated by using the sight distance together with the train speed limit. Sight distance is found using GIS based on the curvature of the railway line assuming a limited field of view, simulating dense vegetation 5m from the railway line. The train velocity is assumed to be constant during the reaction time and the duration of break application, and to decrease linearly during the retardation time. This means that in practice in curves the impact speed equals the speed limit.

The speed limit and the sight distance will differ according to which direction the train is travelling. The potential impact speed is thus calculated in both directions, and the higher of the two results is chosen. The classification of impact speed is set to five different classes, with an impact speed less than 10 km/h resulting in the lowest score of 0, and an impact speed more than 80 km/h achieve the highest score of 10.

The achieved scores for each of the three consequence parameters are finally summarised according to Formula 4, giving every railway segment a consequence score.

$$Consequence\ score = C_{access} + C_{terrain} + C_{speed}$$

Formula 4: Calculation of final consequence score

The consequence score is normalized to values between 0 and 1 for purposes of the risk analysis.

FIELD INVESTIGATIONS

Field investigations were carried out for potential problem areas, identified in the initial stages of the project. The railway sections to include for field investigations are identified from the following sources:

- All sections identified with high-risk potential from GIS-analyses
- Interviews with railway supervisors
- One day overview inspection of the entire mapping area using designated slow-moving train
- Information about historical slides on or near the railway
- Documents describing problem areas

The focus of the field investigations is to evaluate the condition and characteristics of steep side terrain, culverts, railway embankments and river embankments identified as potential hazards.

All segments achieving the highest hazard score of 1 and segments classified with high-risk from GIS-analyses are subjected to a closer inspection in field. The results of the hazard analyses are updated after field investigations, with the hazard scores evaluated in field replacing those calculated by GIS-analyses. In potential risk areas, the GIS-analyses are thus always complemented and adjusted by expert opinion.

RESULTING RISK ASSESSMENT

Risk scores are calculated for all railway segments by multiplying the hazard and consequence score, and categorised into "low", "medium" and "high" risk level, according to Figure 3. This method provides a relative value of risk level for the analysed stretch of railway, allowing for comparison between the railway segments.

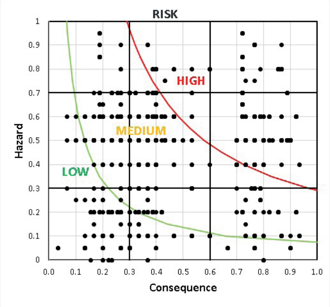

Figure 3: The final hazard and consequence score for every railway segment are plotted together and categorised into “low”, “medium” and “high” risk level

By counting the number of high-risk segments per kilometre railway, one can clearly illustrate where along the railway mitigation measures should be focused (Figure 4).

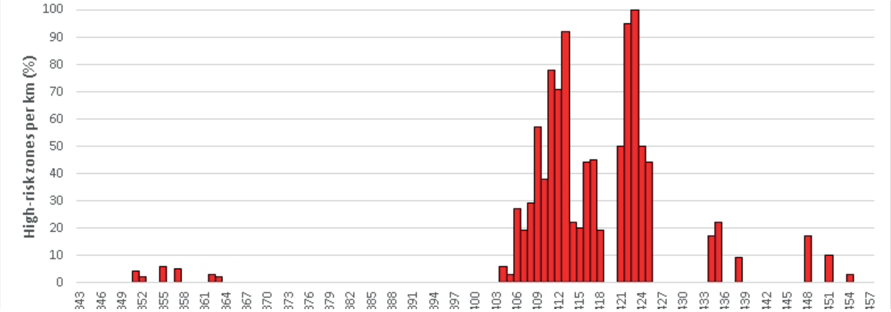

Figure 4: The distribution of high-risk areas per kilometre of railway clearly shows where to prioritise detailed investigations and mitigation measures

All final results are presented in a series of risk maps, covering the complete stretch of railway, each map displaying 1 km of the railway (figure 5). High-risk areas are highlighted in red, showing the decision makers where further investigations are most needed. This is a clear way to communicate information to the end user.

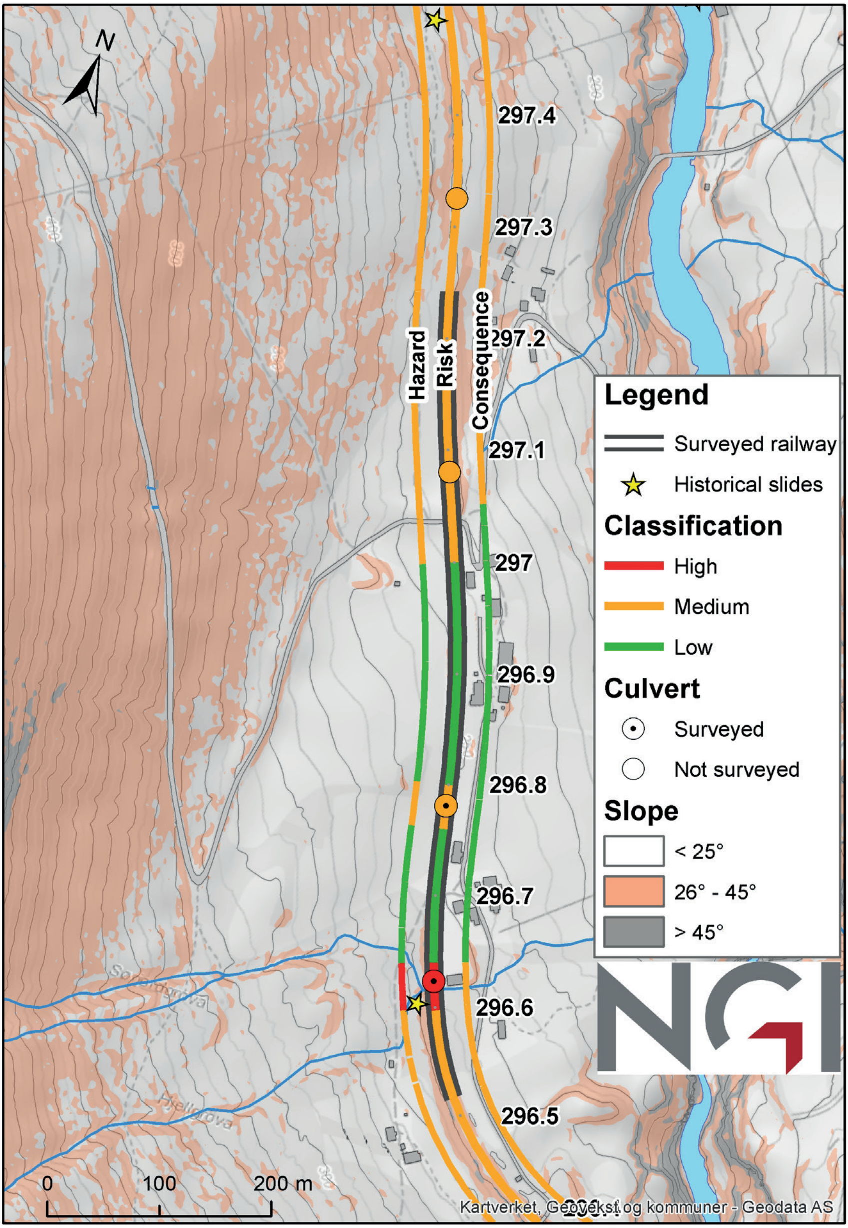

Figure 5: Example of final risk map produced for every 1 km of the analysed railway. The hazard, consequence and risk level along the railway are shown continuously, in addition to risk level of culverts and location of historical slides.

CONCLUSIONS

Advanced analyses through GIS make it possible to conduct a continuous assessment of railway corridors, while fieldwork is focused on closer inspection and evaluation of problem areas. The selection process of these areas is supplemented by information from railway supervisors and other relevant sources. Regional scale mapping of landslide hazard and risk along railway corridors using a GIS based methodology have proven to be a time- and cost-efficient method. The quality of the GIS-analyses is highly dependent on a detailed terrain model of the proximity of the railway. The developed GIS-analyses provide a good indication of the location of potential problem areas, both with regard to the investigated hazards and the consequences of a derailment. It should however be underlined that the GIS analyses serve as a supplement to and not a substitution for field studies.

FURTHER WORK

There are parts of the GIS analysis that could be improved. First and foremost, we see a need to improve the calculation of the expected discharge in connection to culverts by a refined method for estimating the catchment area and extraction of associated parameters. This improvement is planned to be implemented in 2016. Furthermore, the method for estimating collision speed could be refined by taking into account the gradient of the railway line. The accessibility for rescue could take into consideration other factors, especially the type of ground (forest, farmland, bog, etc.).

It is our opinion that the combination of methods presented in this paper identifies possible high-risk areas in a satisfactory manner, with the exception of the hazard relating to insufficient culvert capacity. This hazard type is particularly challenging, as it cannot be properly evaluated using detailed terrain models, overview mapping from inspection train or other available data sources. Performing capacity can only be revealed by a detailed inspection of culvert inlet and outlet. In order to verify the methods regarding culverts, some low- and medium-risk culverts could be randomly selected and examined in field, in order to detect possible underestimations of risk.

REFERENCES

Sweco (2012). Jernbaneverket, Veileder til verktøy for skredfarekartlegging. Report no. 575012/01.