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Road and Rail Infrastructure III

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GEORISK – A RISK MODEL AND DECISION SUPPORT TOOL FOR RAIL AND ROAD SLOPE INFRASTRUCTURE

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Abstract

This paper presents a risk analysis and decision support tool developed for infrastructure assets on both rail and road earthwork networks. This three-stage risk management framework, called GEORISK, is specifically targeted at evaluating slope stability for cutting and embankment assets, focusing on slope stability problems, and is initially being developed for the Irish railway network.
The first step in the framework involves compilation of existing data available to infrastructure owners in a structured database of input parameters that define the controlling variables. This step also involves initial risk modelling to assess the probability of failure of the slope assets. The output of the first stage are probabilities of failure for each of the network's assets.
In the second stage, the probability of failure is subsequently refined using a condition degradation factor that allows non-standard evidence to be incorporated into the analysis. The probability of slope failure is then combined with a vulnerability analysis to determine the consequential impact of the failure. This allows various traffic and loading related factors to be considered.
In the third stage, a slope asset management plan is developed to include mitigation and remediation strategies. This includes a cost benefit analysis (CBA) tool that can be used in parallel with the slope management plan to inform decisions on where expenditure should be focused, offering value for money on annual maintenance budgets.
Overall, the GEORISK tool allows allows the key stakeholders and infrastructure managers to move from a system of reactive maintenance and towards targeted allocation of annual budgets for the highest risk assets.

Keywords: risk management, road and rail networks, geotechnical assets

1 Risk management for slope infrastructure – introduction

Landslide risk management as an interdisciplinary geoscientific topic has been extensively researched from the early 1970's. Recent advances in GIS and other software [1] have made it possible to ease the implementation of the risk management tools over large geographical areas and linear infrastructure networks, thus making them a highly usable tool for infrastructure managers and stakeholders.
Whilst a number of landslide risk assessment and management methods have been proposed, they all follow a similar structure on a macro scale. An example of a typical landslide risk management flow diagram is given in the Figure 1 [2]. Hazard assessments are a starting point for every risk assessment. These deal with characterization of landslide events and the determination of the probability of occurrence of given event. Various approaches can be used to calculate probabilities of failure. A wide range of hazard maps, including landslide inventory and landslide susceptibility maps, are also usually produced as an output, [3, 4].

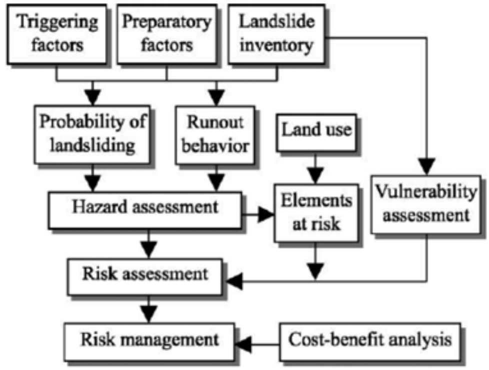

Figure 1 Landslide risk management flow diagram [2]

To complete the risk analysis, consequence analysis that includes vulnerability assessment and identification of elements at risk has to be combined with the hazard assessment, as risk is commonly defined as a product of hazard, vulnerability and elements at risk [5]. Vulnerability assessment defines the degree of loss or damage to a given element at risk affected by the hazard, and takes values on the scale between 0 and 1 [6].

Recent extensive reviews have focused on various levels of risk management like hazard assessment, risk assessment, and full risk management [2], [3], [7]. However, most of the landslide risk management procedures and methods produced have been developed to address the landslides on the natural slopes [8]. Even though the mechanisms of failure are largely the same for engineered slopes, certain aspects of the assessment of infrastructure networks require special consideration. Many major transport infrastructure owners use internally developed risk assessments and management tools, designed to address the specific needs and conditions present on the given network.

In this paper, a risk management model and decision support tool recently developed for cutting and embankment assets on the Irish rail network is presented. The main advance brought by this method is the switch from a visual risk assessment, frequently used by road and rail operators, into a highly sophisticated and less subjective approach with high-end geotechnical calculations taking advantage of data which is available to the infrastructure managers. The risk model is versatile enough to be applied to all rail and road infrastructure networks in general.

2 Risk model Background

The Irish Rail network was among the first rail networks to be constructed with the majority of the network dating back to the mid-1800s. As a result of this, a significant proportion of the network is comprised of aged cuttings and embankments. Like much of the rail infrastructure across Europe, the Irish network predates modern design standards and was built using basic construction techniques and readily mixed local materials. A significant proportion of the network, which has remained stable for over a hundred years, has slope angles far in excess of current design recommendations. Many of these steep slopes are also constructed at angles in excess of the material's natural constant volume friction angle. Their stability is provided by transient suctions which makes them particularly susceptible to rainfall induced shallow failures. In light of changing climate conditions the incidence of slope failures is likely to increase. Therefore to ensure optimum investment, it is imperative that infrastructure managers can quantify the risk represented by individual earthwork assets and rank them accordingly. This will allow for strategic investment to ensure optimum value for Irish Rail in terms of both cost and safety.

3 Stage One – Data requirements and initial risk model

3.1 Data requirements and failure modes

The first phase of the framework is predominately concerned with data collection and subsequent database population. This involves collating existing asset information into a manner which can interface seamlessly with the risk model and compile additional material from external sources. To facilitate this, it is first necessary to identify the parameters critical to earthwork instability for each failure mode considered. This includes not only the geometric and material parameters, but also includes the natural and anthropogenic triggering factors that may lead to instability. Once this has been accomplished the parameters are broken down into lists of known variables and variables which can be inferred based on known parameters. An example of a variable which is known is slope angle. Whereas, an example of a variable which can be estimated with a reasonable level of confidence based off of national soil maps and existing geotechnical knowledge, is the internal angle of friction of a soil. Each parameter will have an associated coefficient of variation which measures the parameter variability. When all variables have been identified, the database is expanded appropriately to account for new variables. The database is then populated using all available resources. In the case of Irish Rail, additional information was gathered from LiDAR scans, national soil maps, national borehole databases, site inspection reports and geological surveys. Naturally, if a parameter is inferred based off of known parameters it's coefficient of variation is increased to reflect its origin.

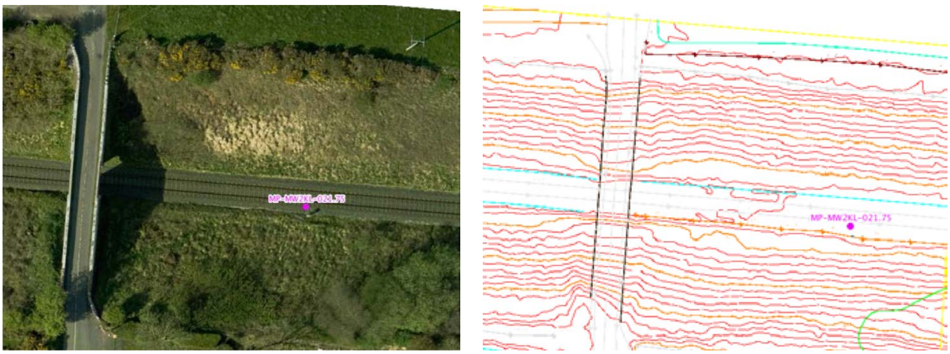

Figure 2 Example of possible various dataset layers gathered from surveys

Soil slopes and in particular rock slopes are susceptible to a wide array of different failure mechanisms. For the purpose of this project a desk study was carried out to determine the failure modes most likely to occur for Irish slopes constructed from glacial till and it was determined that shallow translational slips were most likely to occur due to the large volume of rainfall which occurs annually in Ireland.

However rotational and wedge failures were considered as there is increased consequence associated with these failure modes due to the larger volumes they displace. Shallow translational slides normally result from rainfall infiltration and are generally superficial in nature with the depth of the slide being significantly less than its length, while rotational failures generally occur at depth with an approximately circular slip path. Rotational failures usually arise due to excessive loading in areas with low internal angles of friction or due to some other form of changing boundary condition. They have a much larger volume than translational slides and are usually slow moving. However, in some weak cohesive clays there can be an extremely rapid run-out. Rock slopes on the other hand are more susceptible to wedge failures along pre-existing cracks or faults. These failures vary in magnitude and usually occur rapidly.

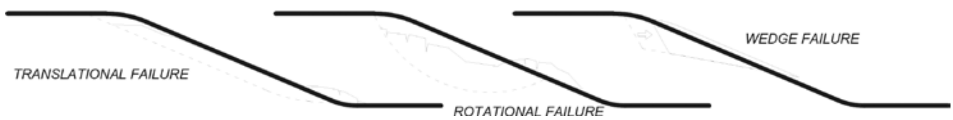

Figure 3 Observed slope failure modes

3.2 Probabilistic Model

Due to the heterogeneous composition of soil, huge variability can exist across relatively small sites [9]. In traditional deterministic analysis, factors of safety are calculated using either the mean parameter values or values slightly less than the mean. However this may not necessarily be conservative, for sites with huge variability this approach can actually overestimate the safety. Using a probabilistic based approach, two slopes which appear identical in terms of geometry and mean geotechnical parameters, could have vastly different probabilities of failure based on their natural variability. Probabilistic tools are extremely useful for extending the service life of existing infrastructure as they give a more accurate representation of stability, allowing designers to classify some assets which struggle to meet modern deterministic safety factors as safe and reliable. Furthermore from an economic point of view it is unfeasible to replace large sections of road and rail infrastructure. Therefore it is necessary to be able to classify the relative risk associated with each asset and fix critical infrastructure first.

In the GEORISK framework, the Hasofer Lind [10] first order reliability method (FORM) is used to calculate the probability of failure associated with each asset and its coupled limit state. The Hasofer-Lind approach is an invariant method for calculating the reliability index β, which can then be transformed into a probability of failure p_f. The first step using this methodology is to transform all variables into normalised random variables. This is accomplished by means of equation (1).

$$\overline{X_i} = \frac{x_i - E[x_i]}{\sigma[x_i]} \qquad (i = 1, 2, \ldots, n) \tag{1}$$

After normalising the variables the next step is to express the limit state in terms of the reduced normal random variables, as in eqn. (2)

$$g(\overline{X}) = g(\overline{x_1}, \overline{x_2}, \ldots, \overline{x_n}) \tag{2}$$

In this reduced variable space the limit state surface $g(\overline{X})=0$ describes the boundary between stable and unstable zones. The Hasofer Lind reliability index in then expressed as the minimum distance between the origin (the mean value of the reduced limit state) and the failure zone. The point on the limit state surface which is closest to the origin is known as the design point. The distance to this point can be described using the following equation (3) [11].

$$\beta_{HL} = \min_{\overline{X} \in \psi} \left\{ \overline{X}\,\overline{X}^T \right\}^{1/2} \tag{3}$$

where:

$\overline{X}$ vector representing the set of reduced random variables;

Ψ failure region defined by letting the performance function $g(\overline{X})=0$.

By constraining this equation the user is able to obtain the reliability of the limit state at the design point. Assuming normal random variables, a probability of failure can then be obtained using the following equation (4).

$$p_f = p\left[g(\bar{X}) < 0\right] = 1 - \phi(\beta) \quad (4)$$

where:

$\phi(\cdot)$ standard normal cumulative distribution function.

Randomly selected assets are then subjected to Monte Carlo simulation for verification.

4 Stage Two – Model refinement and Vulnerability assessment

4.1 Model refinement and Degradation factor

In phase one, the probability of failure is calculated from preparatory variables using inputs like slope geometry and soil types and strength parameters. However, calculation of the probability of failure using this data still does not take account of two important groups of data: the current slope condition and data related to landslide triggering events.
The actual slope response is controlled by variables which cannot be easily described. These variables include data that is usually recorded in a qualitatively manner, such as: type and condition of drainage, type and density of the vegetation, slope erosion and overall condition, etc. Usually they are collected through road and rail infrastructure operators' internal investigations and visual assessments. These factors thus need to be quantified prior to inclusion in the risk model. This is done by introducing the Degradation Factor, which assigns numerical weightings for each qualitative variable and adjusts the probability of failure obtained from stage one. "Hotspots". The past slope history is also accounted for at this stage, allowing previous failures or remediation works to be incorporated into the analysis through an adjustment to the raw P_f. This process also allows the model to be live, with subsequent failures or corrective actions being incorporated into the network wide risk model and the overall relative ranking recalculated accordingly.
Rainfall is by far the most important landslide trigger across Ireland, on the road, rail network or natural landscape. For that reason, rainfall values are considered directly within the database and are inputted in the risk model which will also account for seasonal variability in precipitation. Another triggering input which is included in P_f calculation refinement is surcharge loading.

4.2 Vulnerability assessment

In order to proceed from the hazard assessment done through a refined P_f calculation to risk analysis, a vulnerability assessment must be completed for the elements at risk on the asset network. This analysis includes the cuttings and embankments themselves as well as adjacent objects and structures on the line.
For that reason, information on line ratings, line speeds, the number of tracks, flow, passenger density, and other traffic related data are to be obtained and assigned. The information on adjacent objects' (stations, buildings, adjacent land use) and clearances are also necessary to evaluate the impact of possible landslides. The level of impact can be obtained through the inventory of historical failures and subsequent damage (an example of which is given in the Figure 4), as well as through scenario modelling.

Figure 4 The effects of slope failure of 31/12/2013 on Waterford rail station

Finally, a risk value for each asset can be calculated as a function of hazard and vulnerability assessment outcomes, and the ranked list of assets is compiled.

5 Stage Three – Decision support tool

After the risk values are assigned to each asset, a decision support tool will be developed. This will result in an array of possible answers and procedures for risk reduction. This process will involve some preliminary engineering to develop a slope asset management plan that incorporates generic remediation and mitigation strategies for slopes with different risk profiles. The slope management plan will be developed using an iterative approach that allows the user to test the impact of different maintenance strategies on the long-term risk rating of the assets in the network. Possible scenarios, such as modification of slope geometry, additional geotechnical investigation work for uncertainty reduction, installation of drainage, retaining structures, slope reinforcement, detailed finite element analysis or installation of slope monitoring equipment can be proposed. This will allow the slope management plan to cope with high risk assets that need urgent intervention using hard engineering solutions and also considering more strategic investment decisions that may change the national risk profile (e.g. installing simple drainage on entire set of asset classes).
A cost benefit analysis tool will be developed as an independent module that can be used in parallel with the slope management plan to inform decisions on where expenditure should be focused to maintain minimum safety standards and simultaneously offering value for money on annual maintenance budgets.

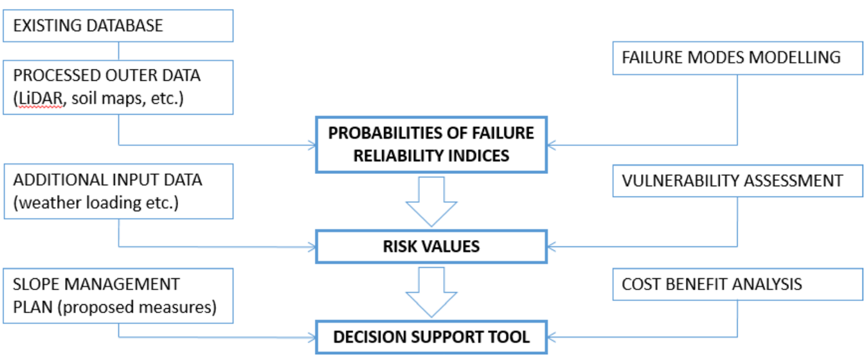

Figure 5 Methodology flowchart

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