Quantitative Landslide Susceptibility and Hazard Analysis for Earthworks on Transport Networks

Martinović, Karlo; Gavin, Kenneth; Reale, Cormac

Publication date
2016

Document Version
Final published version

Published in
Proceedings of the 4th International Conference on Road and Rail Infrastructure

Citation (APA)
Martinović, K., Gavin, K., & Reale, C. (2016). Quantitative Landslide Susceptibility and Hazard Analysis for Earthworks on Transport Networks. In *Proceedings of the 4th International Conference on Road and Rail Infrastructure: CETRA 2016, 23–25 May 2016, Šibenik, Croatia* (pp. 277-283). Article 548

QUANTITATIVE LANDSLIDE SUSCEPTIBILITY AND HAZARD ANALYSIS FOR EARTHWORKS ON TRANSPORT NETWORKS

Karlo Martinović[1,2], Kenneth Gavin[2,3], Cormac Reale[1]
[1] *University College Dublin, School of Civil Engineering, Ireland*
[2] *Gavin & Doherty Geosolutions Ltd., Ireland*
[3] *TU Delft, Faculty of Civil Engineering and Geosciences, Netherlands*

Abstract

Earthworks such as cuttings and embankments account form a major part of the entire transport network infrastructure. Large parts of that infrastructure in Europe are susceptible to a range of geohazards, landslides being the most prevalent. These landslides frequently result in direct damage to assets, deaths and injuries, while indirectly also leading to traffic disruptions. There is a need therefore to identify critical assets where remediation efforts should be prioritised in order to prevent such events from occurring. Current state of the art practice involves using qualitative risk matrices, where the hazard and consequence components are determined through subjective visual survey observations.
Landslide hazard analysis determines the spatial (susceptibility) and temporal probability of landslides of a certain intensity occurring over an observed area. A number of quantitative methods for landslide hazard and risk assessment have been developed recently, generally these methods are considered more effective due to their reduced subjectivity and their consideration of additional factors. A number of studies outline the application of these methods to natural terrain, but to date these methods have not been developed for transport network earthworks. This study presents and compares the results of two landslide susceptibility analysis approaches for cuttings and embankments on a section of Irish Rail network. The first, “geotechnical” approach uses probabilistic slope stability calculations to rank the assets by their reliability index. The second, “statistical” or “data-driven” approach, uses logistical regression as a statistical tool to obtain the susceptibility ranking of the earthworks, using the database of previous failures on the network as an input. Furthermore, several methods for obtaining the temporal hazard characteristics are presented and applied, these methodologies combine to provide a full hazard assessment map of the network.

1 Introduction

Earthwork assets on road and rail network infrastructure are susceptible to a range of geohazards. In many areas including Ireland landslides are the most prevalent type, frequently resulting in direct damage such as fatalities, injuries susceptible and costs connected to asset remediation are high. Additionally, these events incur significant indirect damage such as line closures and traffic disruptions. As the budget available for mitigation and remediation measures is limited, identification of the most critical assets and prediction of consequences of landslides occurring on them is an important task for asset managers and infrastructure operators. This procedure is carried out through the landslide risk assessments, which is a product of landslide hazard (likelihood) and consequence (severity) of landslides on each asset [1]. Current asset managers” practice involves using qualitative risk matrices, where the hazard and consequence components are determined through subjective visual survey observations. However, a wealth of more advanced objective quantitative methods developed for each of the risk assessment subcomponents exists [2-4]. While these aim primarily to natural hillslopes, they can be adjusted to accommodate the specifics of engineered slopes on transport network infrastructure [5]. Examples of spatial and temporal analysis, two main landslide hazard assessment subcomponents, are presented in this paper for the case study of Irish rail network.

2 Landslide susceptibility analyses for Irish rail network

Landslide susceptibility analysis determines the likelihood that a landslide of a certain type will occur for each of the mapping units. It is an initial step toward hazard assessment as it produces a spatial distribution of landslide probability across the study area. Hazard assessment is then derived by combining the susceptibility analysis with the appraisal of landslide magnitude and occurrence frequency. Susceptibility analysis is undertaken using either qualitative or quantitative methods [6]. The latter is further classified into "geotechnical" ("physical") approach based on modelling slope failure processes and "data-driven" ("statistical") approach based on statistical evaluation of the influence of slope attributes on landslide-affected slopes. An application of each approach is presented in this chapter.

2.1 Geotechnical approach

A landslide susceptibility model based on probabilistic slope calculations was developed for cutting and embankments assets on Irish rail network as an initial step towards bespoke risk ranking model and decision support tool [7]. A first step included developing a structured database of geometrical, geotechnical and environmental slope characteristics for every asset. Geometrical characteristics were collated following the processing of LiDAR survey. Soil type was assigned to each asset based on the Geological Survey of Ireland"s soil cover maps using a GIS platform. This procedure was validated using discrete borehole logslocated on the rail network. For each soil type, a typical range of geotechnical parameters was identified from background literature and existing geotechnical reports. This was further complemented by a detailed site investigation for six assets representative of each major soil type (Figure 1).
As the Irish rail network stretches over lengths measured in hundreds of kilometres, large variability in geotechnical parameter values for each soil type can be expected. For that reason, all parameters are described using mean value and standard deviation. This enabled the performance of probabilistic slope stability calculations which give a more accurate representation of stability than standard deterministic approaches. The "Hasofer-Lind" first order reliability method (FORM) [8] was 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. Three limit states reflect the three failure types for which limit equilibrium slope stability calculations were carried out:; (i) shallow translational, (ii) deep rotational slide, and (iii)rock wedge failure (for rock cuttings).
The calculations result in baseline probabilities of failure for each asset. Since these calculations incorporate only simple geometrical and geotechnical data, detailed observations for each asset need to be included in order to account for small differences in landslide-triggering conditions between the assets. This was done by introducing 20 degradation factors (DF) identified through collating site-specific inputs and engineering judgment from IR site inspectors. The total product of DF weights gives the final DF adjustment factor which is combined with baseline reliability indices to obtain final reliability indices and probabilities of failure (Figure 2).

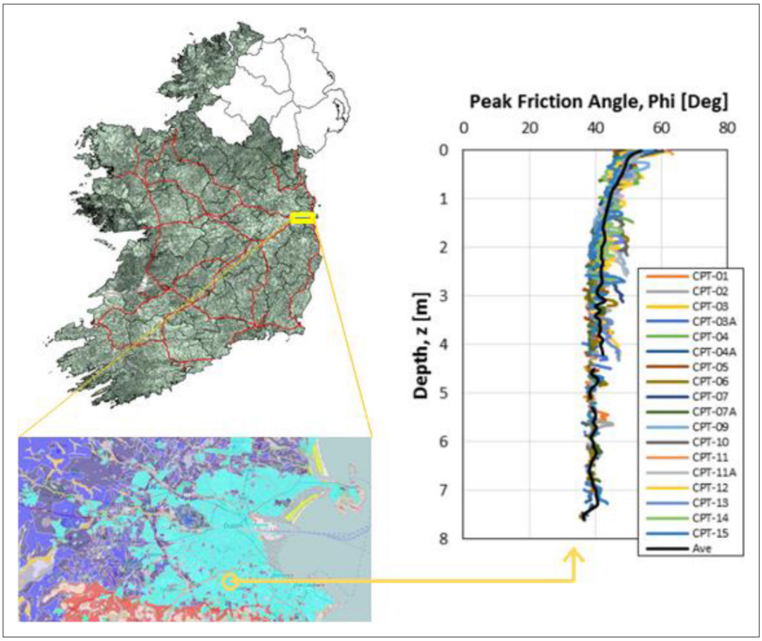

Figure 1 Defining soil types and soil characteristics for Irish Rail earthwork assets (rail lines in red)

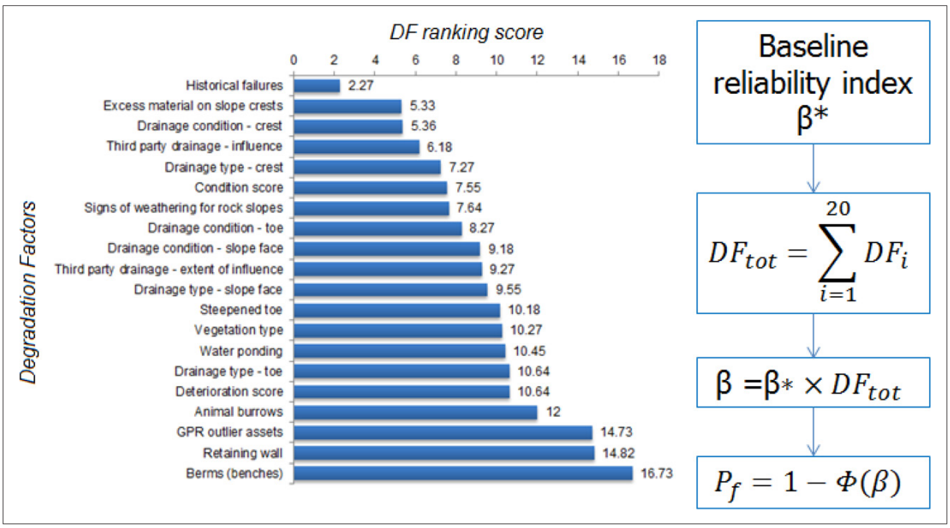

Figure 2 Overview of Degradation Factors and the outline of process for obtaining final probabilities of failure

2.2 Statistical approach

A “statistical” (or “data-driven”) logistic regression method of was used in carrying out the landslide susceptibility analysis on the Athlone Division, a section of Irish Rail network comprising about third of all earthwork assets. The statistical approach uses the historical landslide register to assess the probability of landslide on each asset by quantifying the influence of

topographical, geotechnical and environmental slope characteristics (factors) of slopes from the register. Nine factors that describe the asset have been selected, each with a number of possible classes. The factors are; slope height, slope angle, asset type, aspect, vegetation type, adjacent slope, soil type, annual rainfall and slope conditions.
The goal of logistic regression is to find the best fit model that describes the combined relationship between these factors (independent variables) and the presence or absence of landslides (dependent variable) on all slopes. The final result of this model is a probability p of the landslide occurring, ranging from 0 to 1, for each asset. Comparison of the relative influence on landslides between classes of the same factors can also be inferred from these results (Figure 4). These results for example showed that bare slopes are 4 times more likely to fail than densely vegetated ones, and that west facing slopes are 3 times more likely to fail than the east facing ones. The asset factor database was divided into training set (70 %) using which the model was set up and the validation set (30 %) against which the model results were verified. The performance of the model was interrogated using several statistical measurements such as chi-square test, R^2 test and Receiver Operating Curve (ROC) which showed a very good fit of the model, as did the validation on the validation dataset. Using the calculated probabilities, assets were classified into 5 susceptibility classes: very low (79.4% of all assets), low (13.0%), moderate (3.9%), high (2.3%) and very high (1.4%); effectively identifying and ranking the top critical assets.

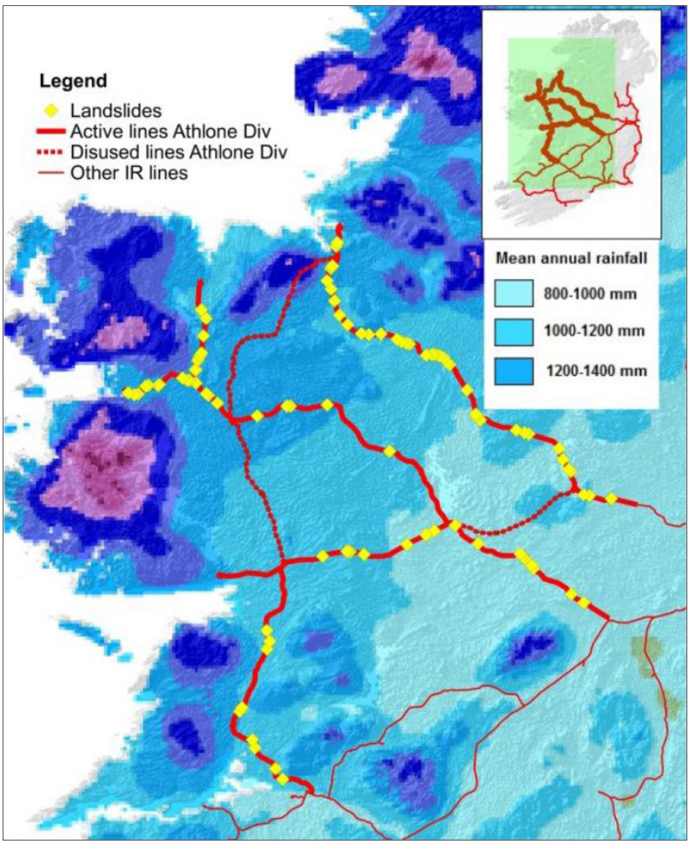

Figure 3 The locations of recorded landslides in Athlone division and mean annual rainfall in study area

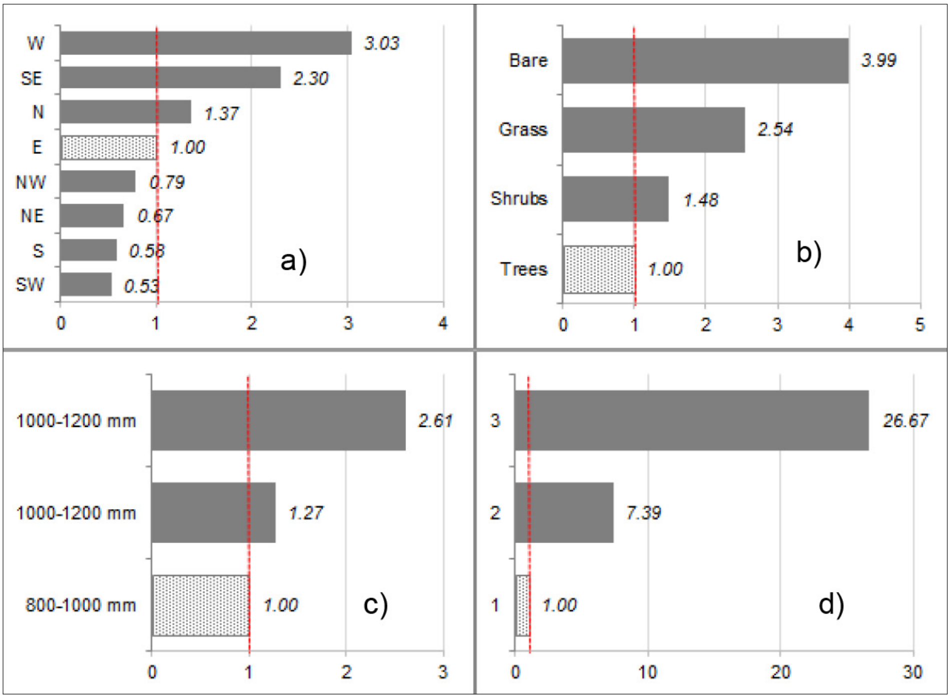

Figure 4 Contribution of each factor class to probability that landslide will occur, relative to the reference class in light grey and denoted with vertical red line for a) aspect, b) vegetation type, c) mean annual rainfall, d) slope condition

3 Rainfall thresholds analyses for Irish rail network

To complete the hazard assessment, the spatial distribution of landslide probability (susceptibility) has to be updated with the temporal analysis of landslide occurrences. The temporal occurrence can be expressed in terms of frequency, return period, or exceedance probability. It is often obtained through statistical empirical analysis of past failures in the study area in a discrete time interval [4]. This approach can also be used to obtain magnitude-frequency curves, jointly assessing the frequency and the size of landslides [9].

Another approach assesses the distribution of landslide trigger events rather than the distribution of past failures themselves. For rainfall-induced landslides, this can be done by defining the rainfall thresholds. Rainfall thresholds represent the lower bound of a combination of some rainfall characteristics such as intensity, duration or accumulation necessary to induce landslides. Two methods exist: “physical”, based on numerical models that take into account the relationship between rainfall, pore pressure and slope stability by coupling hydrological and slope stability models; and “empirical”, based on statistical analysis of the relationship between past failure events and rainfall [10]. Since physical models require very detailed information on soil characteristics, empirical method is much more often used.

Rainfall thresholds using empirical approach have been developed for the landslides that occurred on earthwork assets on the Irish rail network. Landslide records have been obtained from Irish Rail”s landslide register, and rainfall data was provided by the Irish Meteorological Service. In developing the thresholds, several rainfall characteristics combinations have been analysed: rainfall intensity [mm/h] – duration [h], cumulative critical rainfall [mm] – duration

[h], and cumulative critical rainfall [mm] – antecedent cumulative rainfall [mm]. A selection of results is presented in Figures 5 and 6.
Two definitions of critical rainfall event were used to describe the intensity – duration threshold. Both of them result in almost identical thresholds, defined by the power laws $I = 9.5 * D^{-0.75}$ and $I = 6.8 * D^{-0.65}$. These thresholds were found to be lower than most of the thresholds developed for the central and southern Europe [11], attributed to a different climate zone (oceanic climate in Ireland is characterised by more frequent rain events but with lower rainfall intensities). Also, landslide events recorded on Irish rail line earthworks were usually single events, while some of the thresholds collated in [11] only looking at rainfall events causing large number of landslides over a limited area.

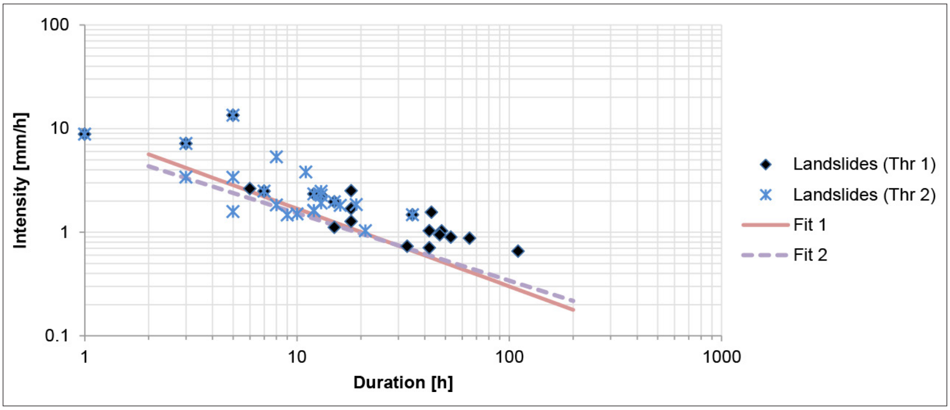

Figure 5 Rainfall intensity – duration threshold

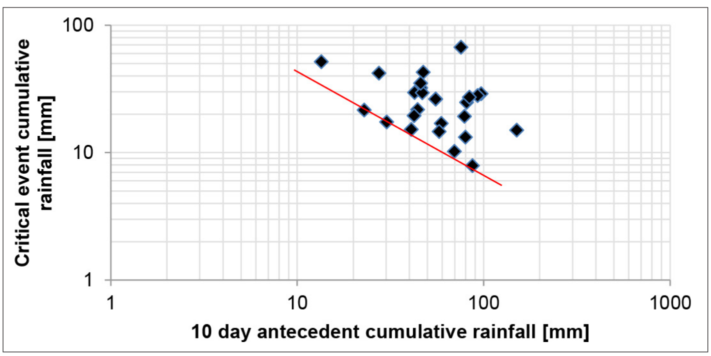

Figure 6 Critical event cumulative rainfall – 10 day antecedent cumulative rainfall threshold

4 Conclusions

Various advanced quantitative landslide hazard and risk assessment methods are in use for natural terrain. These can be adjusted to account for specifics attributed to the earthworks on transport networks, and thus replace the subjective and largely imprecise methods based solely on visual surveys that asset managers currently use. Nevertheless, the data asset managers routinely collect can form an important input in executing quantitative, objective, repeatable and verifiable results.

This paper briefly presents two such methods of landslide susceptibility analysis and a method of carrying out the temporal analysis for the case study of Irish rail network earthworks. The geotechnical approach to the landslide susceptibility is carried out with probabilistic limit equilibrium slope stability calculations for each asset. The statistical approach uses the historical landslide register to assess the probability of landslide on each asset given its characteristics. Temporal analysis is carried out by developing of rainfall thresholds for landslides on the rail earthwork assets in Ireland. Together, these methods give a detailed assessment of landslide hazard over Irish rail earthworks.

Acknowledgment

This work is partly funded by the Horizon 2020 DESTination RAIL Project (Decision Support Tool for Rail Infrastructure Managers) EU Project No. 636285. This research is supported by the Irish Research Council Employment Based Postgraduate Programme scholarship fund. The authors would like to thank Irish Rail for the permission to use this data.

References

[1] Varnes, D.J.: Landslide hazard zonation: a review of principles and practice. No. 3. 1984.

[2] Dai, F.C., Lee, C.F., Ngai, Y.Y.: Landslide risk assessment and management: an overview, Engineering geology 64, no. 1 (2002), pp. 65-87.

[3] Fell R., Ho K.K.S., Lacasse S., Leroi E.: A framework for landslide risk assessment and management, Landslide risk management (2005), pp. 3-25.

[4] Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J.-P., Fotopoulou, S., Catani, F., et al: Recommendations for the quantitative analysis of landslide risk, Bulletin of engineering geology and the environment 73, no. 2 (2014), pp. 209-263.

[5] Jaiswal, P., van Westen, C., Jetten, V.: Quantitative landslide hazard assessment along a transportation corridor in southern India, Engineering geology 116, no. 3 (2010), pp. 236-250.

[6] Aleotti, P., Chowdhury, R.: Landslide hazard assessment: summary review and new perspectives, Bulletin of Engineering Geology and the Environment 58, no. 1 (1999), pp. 21-44.

[7] Doherty, P., Gavin K., Martinović K., Reale, C.: GEORISK–A Risk Model and Decision Support Tool for Rail and Road Slope Infrastructure, Proceedings of the International Conference on Road and Rail Infrastructure CETRA. 2014., pp. 573-579

[8] Hasofer, A.M., Lind, N.C.: Exact and invariant second-moment code format, Journal of the Engineering Mechanics division 100, no. 1 (1974): pp. 111-121.

[9] Hungr, O., Evans, S.G., Hazzard, J.: Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia, Canadian Geotechnical Journal 36, no. 2 (1999), pp. 224-238.

[10] Aleotti, P.: A warning system for rainfall-induced shallow failures, Engineering Geology 73, no. 3 (2004), pp. 247-265.

[11] Guzzetti, F., Peruccacci S., Rossi M., Stark, P.: Rainfall thresholds for the initiation of landslides in central and southern Europe, Meteorology and atmospheric physics 98, no. 3-4 (2007), pp. 239-267.