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Qualitative fault tree for the analysis of slope stability loss in road infrastructure

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Abstract

Landslides are natural hazards all over the world, being the loss of slope stability in transport infrastructures considered small-scale landslides causing economic and human losses. Although there are many examples in the literature for the general analysis of landslides susceptibility, little information is available to analyze slopes at a local scale. The objective of this work is to identify all the slopes in road infrastructure, select those located in landslide susceptibility areas and apply a qualitative fault tree, also defined in this work, to determine the factors which can cause the slope stability loss. The results obtained are useful for infrastructure managers to have an inventory of all the slopes and to have a tool (failure tree) to identify the factors that influence each critical slope.

Keywords: Fault Tree; slope; transport infrastructure; loss of stability; landslide.

1. Introduction

Landslides are natural hazards all over the world. Particularly for Europe, the human and economic losses due to landslides from 1995 to 2014 have been 1,370 deaths and 4.7 billion Euros (Haque et al., 2016). Transport infrastructures are areas where both economic and human losses are high due to delays, injuries, and rehabilitation (Martinović et al., 2016; Miele et al., 2021). The areas of transport infrastructure most prone to landslides are slopes, whose loss of stability can be considered small landslides that may cause serious accidents (Martinović et al., 2016; Smethurst et al., 2017).

Many works are available for the general analysis of landslides susceptibility, considering and weighting factors that influence landslides using different methods, thus achieving landslides susceptibility maps. Some works that can

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be highlighted are the following: Akgun (2012); Kavzoglu et al. (2014); Lee & Pradhan (2007); Pradhan & Lee (2010); Yalcin (2008). However, little information is available to analyze slopes at the scale of transport infrastructures. Some works that studied these slopes are the following.

Glendinning et al. (2014) presented the results of 4 years of controlled experiments on a full-scale embankment model, to demonstrate the relative influence of weather events on the fluctuations of pore water pressure. Tang et al. (2018) also identified climate-driven processes, together with vegetation processes, as those expected to change in incidence and severity affecting slope stability of new and existing infrastructure. Different factors were highlighted by Che Mamat et al. (2019), who studied factors that contribute to the stability of soft ground of the road embankments, stating that settlement, slope stability, and soil bearing capacity are important to constructing the road embankment. A general list of important factors that should be considered for engineered slopes on a rail transport network was proposed by Martinović et al. (2016), who also examined the suitability and effectiveness of statistical data-driven landslide susceptibility methods for those types of slopes.

A numerical analysis has been performed by Murad Hasan & Chowdhury Ankan (2020) to compute the factor of safety and shear strength of slope soil with and without vegetation roots. This numerical analysis also made it possible to observe the effect of different types of vegetation on slope stability. Also emphasizing the importance of the root, the review by Stokes et al. (2009) discussed root traits in the context of slope stability, providing useful information for landslides engineers. Finally, Smethurst et al. (2017) reviewed the current role of instrumentation and monitoring in engineered slopes, including the reasons for monitoring infrastructure slopes, the instrumentation typically installed, and the parameters measured.

Although the above works analyze slopes at a local scale, some of them focus on specific factors. For this reason, this work will review all factors which influence the loss of stability by constructing a qualitative failure tree. A fault tree is a graphical model that describes the relevant faults that might occur in a system and the interaction of these faults that can cause a failure in the whole system. The structure of a fault tree consists of two types of nodes: events and gates. Events are usually the failures of a subsystem and gates represent how these failures propagate through the system. Fault tree analysis can be qualitative (used to detect system vulnerabilities) and quantitative (used to derive failure probabilities) (Ruijters & Stoelinga, 2015).

The following describes works that have used fault trees in the context of slopes. Li et al. (2011) presented a probabilistic fault tree approach for system reliability evaluation of rock slope involving multiple correlated failure modes. The work carried out by Kazmi, Qasim, Harahap, Baharom, et al. (2017) analyzed the need for human reliability in geotechnical aspects and developed a failure tree of significant scenarios responsible for slope failures to minimize the effect of the consequences. Similarly, as in the previous work, Kazmi, Qasim, Harahap, & Baharom (2017) used a fault tree analysis to quantify the causes of human error in a Malaysian landslide case study, determining the probabilities of landslides occurring with different events. Also in a case study in Malaysia, Kazmi, Qasim, Harahap, & Vu (2017) used fault tree analysis to trace the factors contributing to a pipeline burst that triggers a landslide. Lastly, Usman et al. (2021) used fault tree analysis to identify the factors associated with drainage failure of ballasted railway tracks that contribute to railway drainage flood risk.

Although they use failure trees, the previous works do not provide failure trees with all the factors that can influence the loss of stability on a road slope. In this work, a failure tree will be constructed with the factors affecting slope stability, which have been previously reviewed and classified from the existing literature. The objectives of this work are the following:

- Identify all the slopes in a road infrastructure
- Select slopes located in landslide susceptibility areas
- Apply a qualitative fault tree, also defined in this work, to determine the factors which can cause the slope stability loss

2. Methodology

The general workflow in this work is shown in Figure 1.

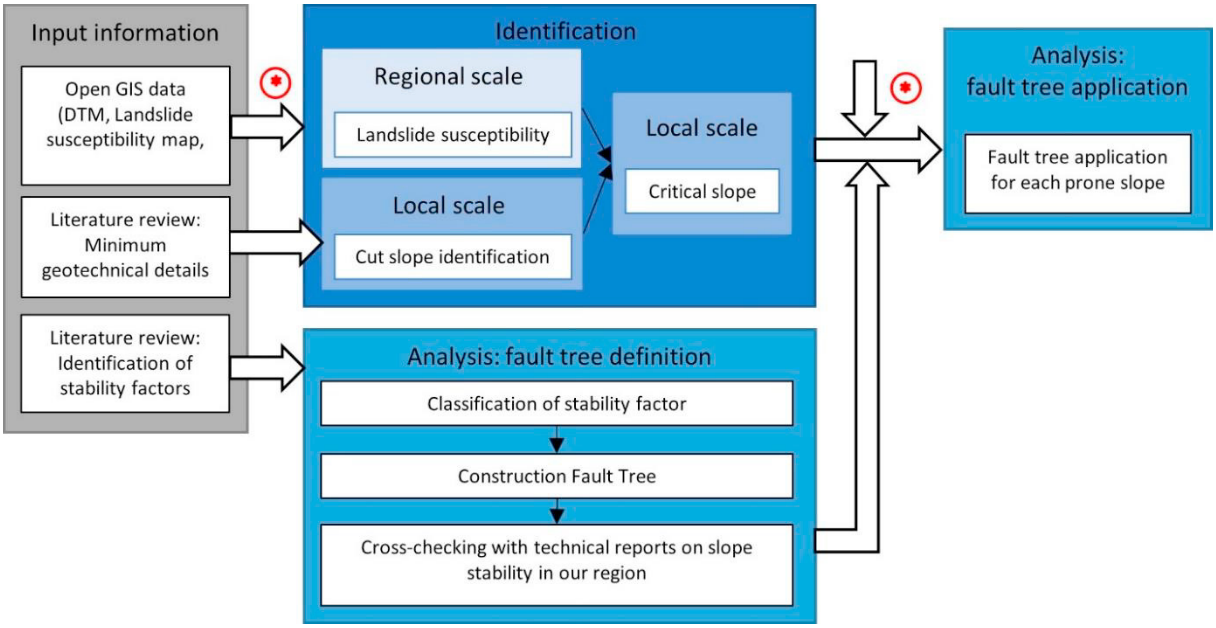

Figure 1. General methodology.

The first step consists of the collection of information, mainly from public sources. This information acts as an input to the other two steps. The second step is the identification at the local scale of the slopes in a road infrastructure considering their geometric characteristics. Slopes located in landslides susceptibility zones at a regional scale have been selected and defined as critical slopes. The last step consists of the definition and application of a fault tree analysis. For the definition of the fault tree, several factors have been identified and classified from the literature. Using these factors, a qualitative fault tree is built to identify potential causes of slope failures (Gestión Del Riesgo. Técnicas de Apreciación Del Riesgo, 2011). The final failure tree is obtained by cross-checking the factors identified and classified from the literature with the factors identified as critical in various slope stability technical reports obtained from infrastructure managers in our region of interest (NW Spain). The application of this final qualitative fault tree to each critical slope consists of identifying factors affecting each slope that is considered in the fault tree.

2.1. Input information

The materials used in this work are information that is in the public domain and is explained in the following Table 1.

Table 1. Information used in this work.

Type of information	Definition	Format of data	Source
Elevation	Digital Terrain Model (DTM) with 2-metre resolution	Raster	(Gobierno de España: Ministerio de Transportes, Movilidad y Agenda Urbana. Centro de Descargas Del CNIG (IGN))
Infrastructure data	Road infrastructure	Shape layers	(ArcGIS Hub. Puntos Kilométricos de España)
Landslide susceptibility mapping	ELSUS-European Landslide Susceptibility Map	Raster layer	(Wilde et al., 2018)

The literature review is necessary to define the geotechnical details of the slopes, i.e. the minimum gradient, length, and height to be considered as a slope. Several references have been reviewed and the mean has been calculated with all the minimum geotechnical details considered for the slopes in each work (Department of Transport and Main

Roads, 2020; Glendinning et al., 2014; M. A. Hicks & Spencer, 2010; Michael A. Hicks & Li, 2018; Jayapal & Rajagopal, 2010; Ji & Chan, 2014; Suh et al., 2011; Yingchaloenkitkhajorn, 2019). The values obtained and to be considered in this work are as follows: 40º for gradient, 60 meters for length, and 6 meters for height.

Once the minimum geotechnical details for slopes are defined, the factor that affects the stability of slopes should be established. These factors are also extracted and classified from the literature review, being the following references used: Ayala Cercedo & Andreu Posse (1988); Che Mamat et al. (2019); Garnica Anguas et al. (2017); Glendinning et al. (2014); Martinović et al. (2016); Murad Hasan & Chowdhury Ankan (2020); Plenes et al. (2014); Scaioni et al. (2014); Stokes et al. (2009); Tang et al. (2018). These factors were classified and used to construct the fault tree shown in Figure 2 in the results section.

2.2. Identification

This step consists of identifying at the local scale the critical slopes in road infrastructure, defined as those slopes located in landslide susceptible zones at the regional scale (Wilde et al., 2018). First, all slopes of the road infrastructure that fulfill the minimum geotechnical details defined in the previous section are identified at the local scale in the Digital Terrain Model. In this way, an inventory of all the slopes of the road is obtained. With all slopes identified, the critical ones are selected being those located in zones of high and very high susceptibility maps (Wilde et al., 2018).

This study will focus on analyzing slopes in three motorway stretches located in the south of Galicia (northwest Spain), which have already been identified as being prone to landslide risk in previous academic work. Stretches considered are as follows: two stretches of 30 and 18 kilometers of A-52 Motorway, and the whole AG-31 Motorway with a length of 18 kilometers. The location of the region and stretches of the motorway considered are shown in Figure 3-C.

2.3. Analysis

The analysis is developed in two stages: fault tree definition and fault tree application.

With all stability factors identified in the literature review, a classification is made before the construction of the fault tree. This tree is cross-checked for our region, applying it to several slope stability technical reports to check whether all possible factors are being considered. This only has the function of checking whether all factors are being considered, it is not intended to eliminate factors that are not common in our region. An example of this is that it was found that in our region the most common triggering factor is rainfall and the least common is volcanoes. However, volcanoes are not discarded, as the fault tree would not be applicable to other regions.

With the fault tree developed, it can be applied to all critical slopes. In this way, it is tested how many factors of the fault tree are involved in each of the critical slopes. This application step is similar to the cross-check step.

3. Results

The results obtained in this work can be separated into three.

The first result obtained is the fault tree. Two fault trees were constructed, which were embedded in a flowchart, as seen in Figure 2. The first fault tree deals with the geotechnical details of the slope and with the triggering factors. The geotechnical details provide information about the types of slopes and the triggering factors provide information about factors that can produce a loss of stability in those slopes. If the geotechnical detail does not fulfill the minimum requirements and there is not any triggering factor, there is no instability. Otherwise, if both fulfill, it may be checked if there are other factors involved. For this, the second fault tree deals with conditioning factors, which are divided into geology and human activity.

The second result consists of obtaining the critical slopes in the road. For this purpose, and considering the minimum geotechnical details, all slopes were identified in our case study. The slopes located in areas of high and

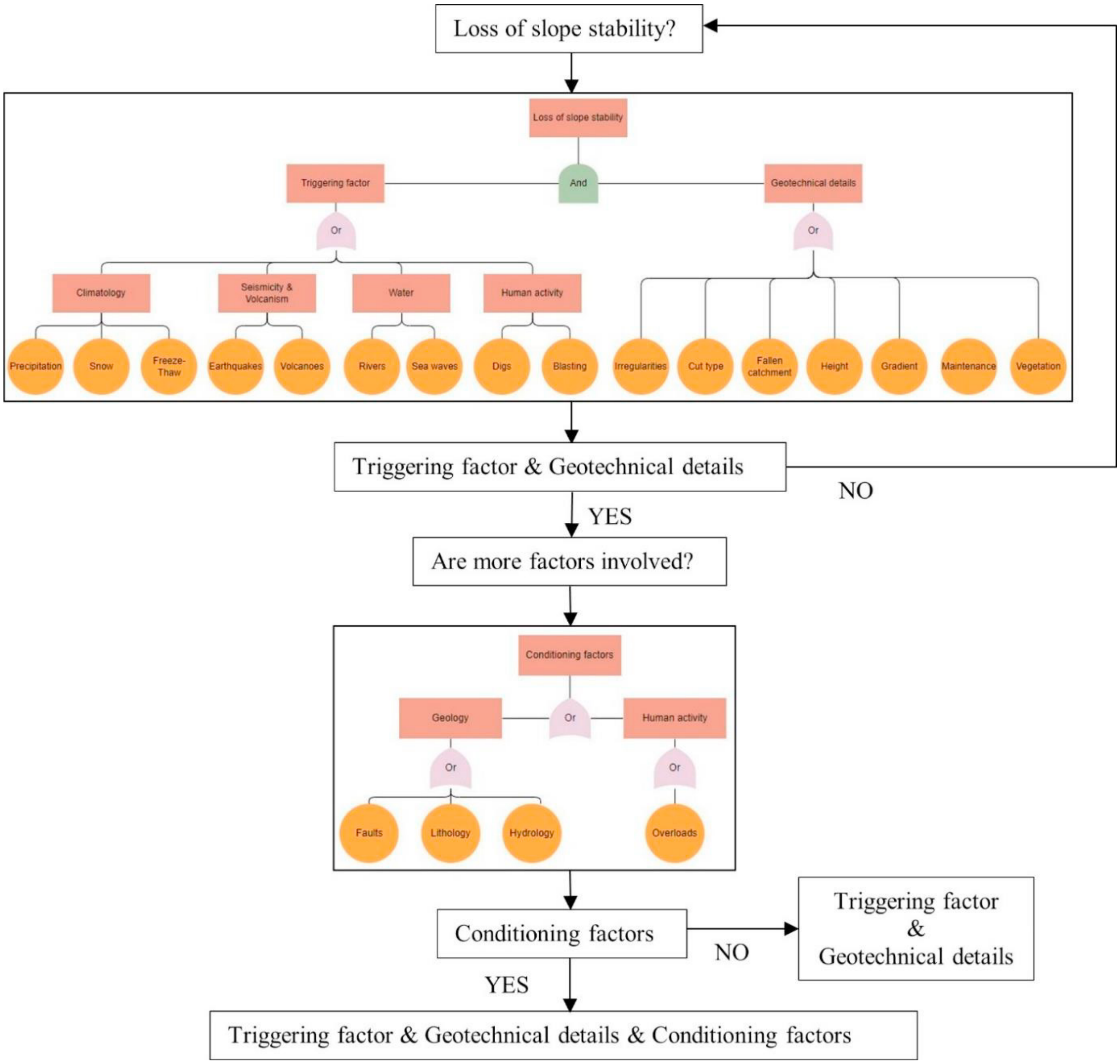

Figure 2. Fault trees embedded in flow diagram.

very high landslide susceptibility maps were considered critical slopes. This is shown in Figure 3, where B is the landslide susceptibility map (ELSUS), C is the inventory of slopes and D are some of the critical slopes.

The third result is the application of the flowchart with the fault trees embedded in each critical slope. This result allows simple and quick identification of the factors in the fault tree that affect each critical slope, thus obtaining an inventory of all the critical slopes and the factors that affect them.

4. Discussion

Once a preliminary fault tree was constructed, it was cross-checked with several case studies collected in technical reports provided by the infrastructure managers. This cross-check serves to verify whether the factors affecting slopes

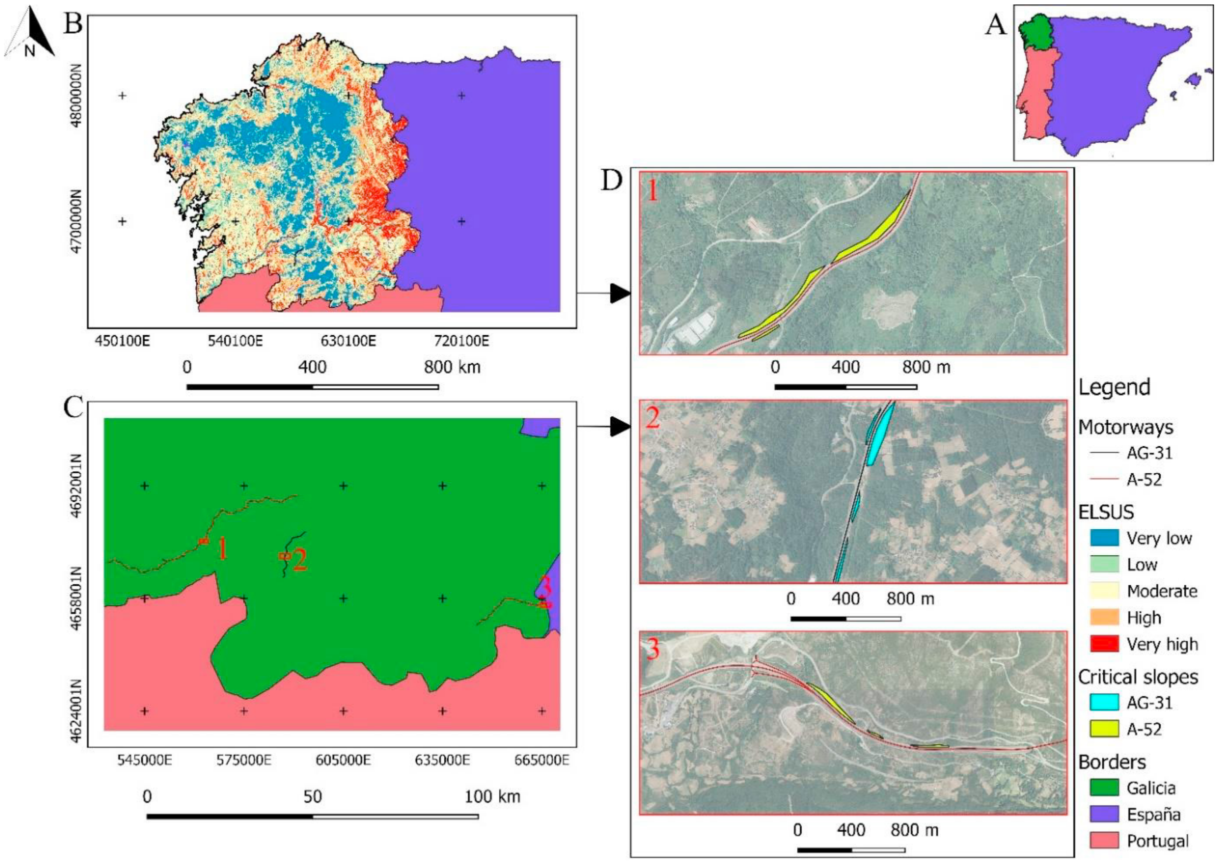

Figure 3. Results obtained. A) general location of our region of study (NW Spain); B) landslide susceptibility map (ELSUS); C) Inventory of slopes in the stretches of motorways considered; D) Some examples of the critical slopes.

in our region are covered in the fault tree and none of them are missing. The intention of the cross-check is no adapt exclusively the fault tree to our region but to check that slopes in our region are covered under the application of the fault tree.

It is important to mention that some factors are considered in a general way and must be adapted for each specific region. This is the case of lithology, which is not subsampled in all their possible classes as this would make the tree too large.

Application of the fault tree is done similarly as the cross-check. It is observed that the fault tree is a quick and easy method to check the factors affecting the stability of a road slope, thus providing an inventory of slopes and their factors so that infrastructure managers can make decisions regarding maintenance tasks, both predictive and corrective.

Focusing on the discussion of our results in comparison to previous works, our fault tree considers the loss stability factor on the road at local scales: the minimum slope considered is 40° for the gradient, 60 meters for the length, and 6 meters for the height. None of the previous work revised and mentioned in the introduction constructs a fault tree from this point of view.

Many works considered stability factors at the landslide scale, but they did not elaborate a fault tree but created susceptibility maps (Akgun, 2012; Kavzoglu et al., 2014; Lee & Pradhan, 2007; Pradhan & Lee, 2010; Yalcin, 2008). Some works have studied the loss of slope stability in roads on a smaller scale, studying various factors that affect slope stability (Che Mamat et al., 2019; Glendinning et al., 2014; Martinović et al., 2016; Murad Hasan & Chowdhury Ankan, 2020; Smethurst et al., 2017; Stokes et al., 2009; Tang et al., 2018). However, none of the works have considered all the factors that can affect a road slope or classified them to construct a failure tree.

Other works also have studied factors affecting slopes considering the fault trees. Li et al. (2011) present failure modes and not factors influencing the loss of stability. Kazmi, Qasim, Harahap, Baharom, et al. (2017) only consider human causes and present different scenarios in the failure trees. Kazmi, Qasim, Harahap, & Baharom (2017) also only consider human causes and apply them to a case study, as well as the work of Kazmi, Qasim, Harahap, & Vu (2017), where the fault tree is also particularized for a very specific human factor, which is the bursting of a pipe. The fault tree proposed by Usman et al. (2021) also focuses on a very specific aspect, the drainage flood risk. These do not provide failure trees considering all factors and classifying them in a generic way so that they can be applied to any slope as in this work.

5. Conclusions

In this work, we presented a methodology for the identification of slopes and the factors which can cause their loss of stability in road infrastructure. This methodology consists of collecting information, identifying slopes, and defining a qualitative fault tree to be applied to critical slopes, defined as those located in landslide susceptibility zones and with minimum geotechnical details. The results obtained can be divided into three categories:

- Inventory of all slopes in a road and selection of the critical ones
- General qualitative failure tree for the identification of potential causes of slope failure
- Qualitative fault tree for each slope

These results are useful for infrastructure managers to recognize all the slopes in the infrastructure and to obtain a qualitative fault tree with the factors affecting the loss of stability in each critical slope. This knowledge is crucial to making decisions on the maintenance works.

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