

EVALUATION OF LANDSLIDE PREVENTIVE MEASURES ON ROADSIDE SLOPES

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Abstract

Landslides of road slopes stand for phenomena resulting in minor to even catastrophic consequences, with impact on road infrastructure and road users. Moreover, properties next to the road may be affected as well. Nowadays, these phenomena occur more and more frequently and their impact becomes more and more higher, due to climate change and forest fires. Thus, adequate preventive measures, are of utmost importance in the context of safety guarantees.

The present paper defines and analyses criteria, such as implementation cost and ease of establishment, implementation range and effectiveness, for appraising measures of landslide prevention, conducting an analytical hierarchy process scheme. A thoughtful set of the appraisal criteria is considered to be a cornerstone for correct and comprehensive evaluation. The preventive measures are selected from most common ones, such as slope change, drainage infrastructures and planting. Results may vary according to special characteristics of each potential landslide field. Evaluation of each criterion may also vary according to the climatic and economic environment in which the appraisal is conducted. In this frame, a measure which is indicated as optimal for a certain study area may be inadequate for another area.

Given the aforementioned, the results show fruitful and interesting findings, attributing scores to the examined measures, in terms of overall and each criterion evaluation. The appraisal methodology presented, may be used as a tool for road operators and competent authorities, so as to assess the most effective preventive measures, with respect to inherent and general characteristics that apply in each case.

Key words: *Roadside slopes, landslides, appraisal, preventive measures, evaluation*

Introduction

Road slopes are arranged along the entire length of each road infrastructure and their integrity is directly linked to the proper functioning of the road axes, as their deformation or destruction leads to traffic problems, for commercial, professional and tourist purposes. Therefore, it is the duty of road network managers to ensure their maintenance or formation and to take preventive measures for this purpose.

Roadside slope landslides are a phenomenon that may occur due to natural causes, such as heavy rainfall, snowfall, natural disasters (e.g. earthquake) or to anthropogenic causes (e.g. tunnel construction) or felling of trees on the slope (Figure 1).

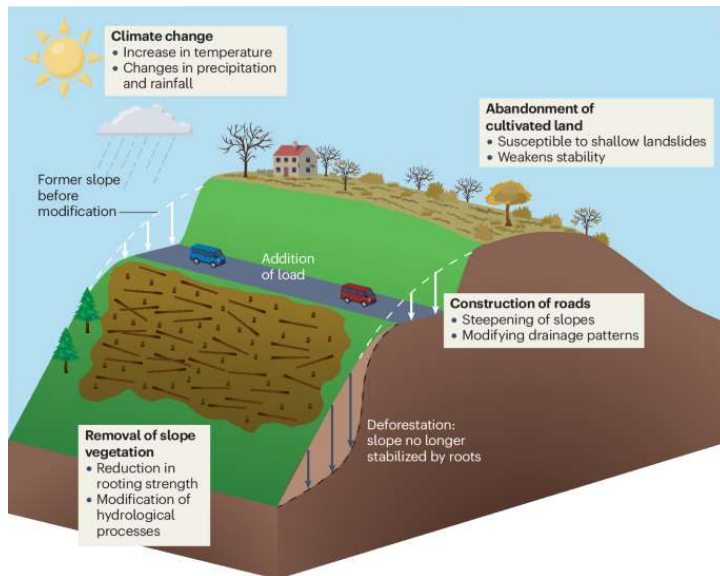


Figure 1: Consequences of slope deforestation (Hill et al., 2024)

The effects of landslides can be very significant, such as the interruption of traffic or even the complete destruction of part of the road network in an area (Figure 2), resulting in the hard movement of vehicles. Secondary consequences include difficulties in traffic, which may be devastating for the economic activity of the area and in other cases, may even pose a risk to the lives of residents, as access to health facilities becomes difficult or impossible, depending on the case and the magnitude of the landslide. Erosion of the slope can even cause dangerous situations for the buildings in the area (Alamanis et al., 2020; Ecoslopes, 2004), since it can lead to erosion and movement of the soil (Figure 1). In our time, landslides are more frequent due to intense or extreme climatic phenomena and forest fires.



Figure 2: Landslide hazards (<https://www.climatechangepost.com/news/on-a-global-scale-landslide-hazard-doesnt-seem-to-be-increasing-due-to-climate-change/>)

Landslide prevention measures on road slopes can lead to the avoidance or reduction of these unpleasant effects. For this reason, their implementation before the occurrence of a landslide is of utmost importance.

An important issue that needs to be examined is the effectiveness and cost of implementing these measures. In other words, is it scientifically correct to implement a

landslide prevention measure that does not adequately ensure what it was designed for? In addition, the economic aspect of each prevention measure should be examined, as the amount of human and financial resources required is not unlimited and in some cases is quite restrictive.

Taking the above into account, this study presents a methodology for evaluating three of the most common landslide prevention measures, namely terraced slopes (Figure 1), drainage infrastructure (Figure 2) and planting (Figure 3). Thus, the goal is to find the optimal choice, taking into account the specific characteristics and economic environment of each case.



Figure 3: Terraced slopes (<https://en.jardineriaon.com/how-to-make-sloping-terraces.html>)



Figure 4: Drainage infrastructure (Hearn and Hunt, 2011)



Figure 5: Planting (<https://landscapearchitecturemagazine.org/2018/04/24/slope-style/>)

Considering the above, a tool, meaning a concise methodology for selecting the optimal measure for landslide prevention, is necessary for road operators, so as they can conclude,

which is the best preventive method for preventing catastrophic consequences on the road network, without spending excessive or useless resources. This is exactly what the present study deals with, by proposing a simple and comprehensive optimal choice selection methodology for road operators and constructors.

Methodology

The proposed methodology for the evaluation of alternative measures to prevent landslides on road slopes is that of the Analytical Hierarchy Process (AHP) (Saaty, 2006; Saaty, 2008). This method was chosen in order to take into account the specific characteristics of each case during the evaluation, as relevant studies for engineering tasks have demonstrated (Papageorgiou, 2020; Papageorgiou, 2022; Papageorgiou et al., 2019; Papageorgiou et al., 2020). For example, a road slope that is rocky is very different from another that is clayey, both in terms of the ease of implementing a prevention measure and the cost of implementation. At the same time, each alternative measure requires different amounts of human resources, equipment, materials and project machinery.

To conduct the evaluation using the AHP method, five criteria were used, namely implementation cost, ease of application, versatility, effectiveness and environmental adaptation. Thus, the evaluation scheme is presented in Figure 6.

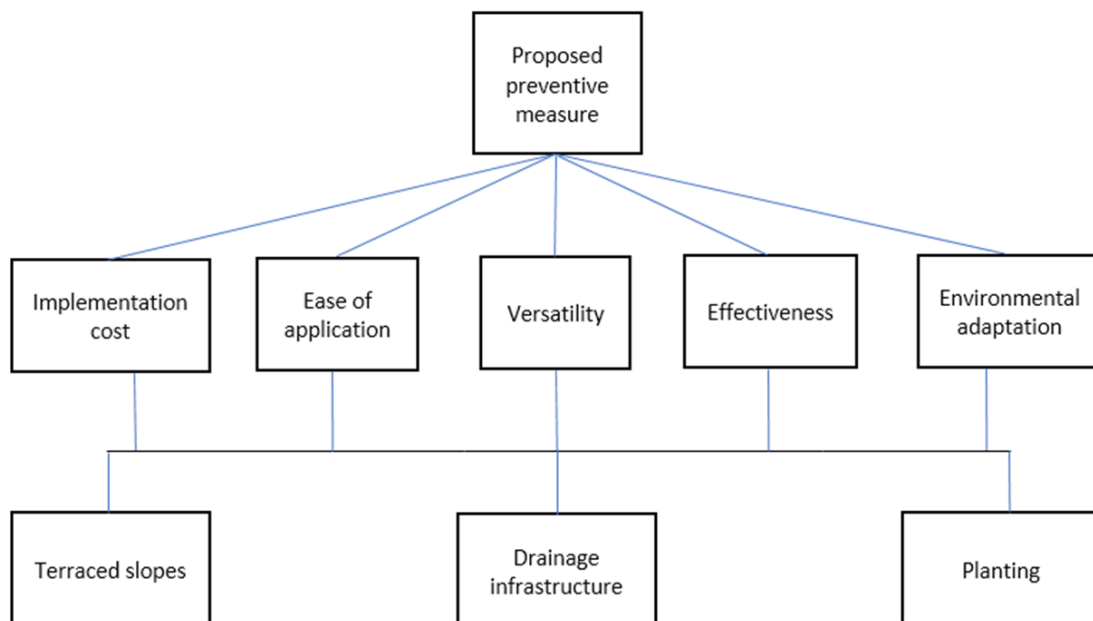


Figure 6: Evaluation scheme

In order to carry out the evaluation, a clear description of the evaluation criteria is shown in Table 1. The description was drawn up with the aim of including as fully as possible all the factors that influence the implementation of such a project, as well as its impact to the natural and anthropogenic environment.

Table 1: Description of evaluation criteria

Appraisal criteria	Description
Implementation cost	Cost of application, including machinery, personnel, timeline and required resources, considering location, time and special characteristics of each case
Ease of application	Availability of equipment and materials, range of laying temperatures, familiarity with the technique and possible or current rates of application
Versatility	Field of its application, the range of geological and slope segments targeted (e.g. high differentiation of slope values, rock, clay, sandy ground)
Effectiveness	Expected engineering result of the implemented technique, the slope performance after operations
Environmental adaptation	Effects on the environment and degree of adaptation in the natural landscape

A clear description of the criteria is important so that the evaluation can be carried out within a specific and clear framework. Furthermore, it includes all the important elements that must be taken into account so that the resulting result is reliable and holistic, i.e. takes into account the specific characteristics and the available budget.

Results

The three alternative landslide prevention measures examined in this study are evaluated for their adequacy in the criteria that have been established, following a search in the literature and relevant applications (Guzzetti et al., 2015; Pérez-Maqueda, 2019; Capobianco et al., 2025; Maes et al., 2017; Alcántara-Ayala and Sassa, 2023; Schuster and Highland, 2011; Alexiou et al., 2020; Neumann and Calliari, 2016; Lan et al., 2020; Zacharof, 2011). The results of this research are shown in Table 2.

Table 2: Evaluation of preventive measures

PREVENTIVE MEASURE	IMPLEMENTATION COST	EASE OF APPLICATION	VERSATILITY	EFFECTIVENESS	ENVIRONMENTAL ADAPTATION
Terraced slopes	Low / Fair (low construction budget)	Very good (Simple equipment, various techniques of application, fast construction time)	Good (not applicable in rocky or loose soils)	Good (reduced function in certain cases)	High (minimum intervention in the natural landscape)
Drainage infrastructure	High (costly materials and works)	Good (Complex equipment, specialized personnel, slow application rate)	Very good (applicable in most cases)	Very good (long-term reliability)	Low (major intervention in the landscape)
Planting	High (costly plants, tasks and care)	Good (Large number of specialized personnel, slow application rate)	Very good (applicable in most cases)	Very good (immediate restoration of stability)	Excellent (environmental enrichment)

Assessing different evaluation methods through comparative analysis is certainly a challenging endeavor. However, there are specific distinct differences that illustrate the advantages and disadvantages of each method in relation to the others.

Based on the findings of the above research, the application of the AHP method with pairwise hierarchy was carried out. The results are shown in Table 3.

Table 3: Pairwise comparison of alternatives with respect to the evaluation criteria

Implementation cost	Terraced slopes	Drainage infrastructure	Planting	Priority
Terraced slopes	1	3	4	0.625
Drainage infrastructure	1/3	1	2	0.238
Planting	1/4	1/2	1	0.137
Ease of application				
Terraced slopes	1	3	3	0.600
Drainage infrastructure	1/3	1	1	0.200
Planting	1/3	1	1	0.200
Versatility				
Terraced slopes	1	1/3	1/3	0.143
Drainage infrastructure	3	1	1	0.429
Planting	3	1	1	0.429
Effectiveness				
Terraced slopes	1	1/3	1/3	0.143
Drainage infrastructure	3	1	1	0.429
Planting	3	1	1	0.429
Environmental adaptation				
Terraced slopes	1	5	1/4	0.231
Drainage infrastructure	1/5	1	1/9	0.060
Planting	4	9	1	0.708

The alternative prevention measures present different priorities, with regard to implementation cost, ease of application, versatility, effectiveness and environmental adaptation.

Then, a comparative ranking is made in pairs for the evaluation criteria, as shown in Table 4. The effectiveness of the appropriate measure is considered the most important criterion. They follow in hierarchical order, implementation cost, versatility, effectiveness and environmental adaptation and lastly ease of application is ranked. It is crucial to recognize that the significance of each criterion and the assessment of every prevention measure should be determined by qualified engineering professionals, taking into account the unique characteristics of each situation along with the budget and any additional limitations. If specific insights must be derived from the roadside slope, the methods that meet or do not meet the desired outcomes should be appropriately assigned relative importance weights.

Table 4: Pairwise comparison of the evaluation criteria

Evaluation criteria	Implementation cost	Ease of application	Versatility	Effectiveness	Environmental adaptation	Priority
Implementation cost	1	3	1	1/5	1	0.129
Ease of application	1/3	1	1/3	1/7	1/3	0.051
Versatility	1	3	1	1/5	1	0.129
Effectiveness	5	7	5	1	5	0.563
Environmental adaptation	1	3	1	1/5	1	0.129

The overall weights of the prevention measures are listed in Table 5 and the results of the overall evaluation are shown in Figure 7. First is the Planting measure, second is Drainage and third is Terraced slopes. According to each scenario, adequate pairwise comparison weights should be attributed.

Table 5: Overall weights of preventive measures

Preventive measure	Priority with respect to					Overall priority / score
	Implementation cost	Ease of application	Versatility	Effectiveness	Environmental adaptation	
Terraced slopes	0.080625	0.0306	0.018447	0.080509	0.029799	0.23998 (~24%)
Drainage infrastructure	0.030702	0.0102	0.055341	0.241527	0.00774	0.34551 (~34.5%)
Planting	0.017673	0.0102	0.055341	0.241527	0.091332	0.416073 (~41.5%)

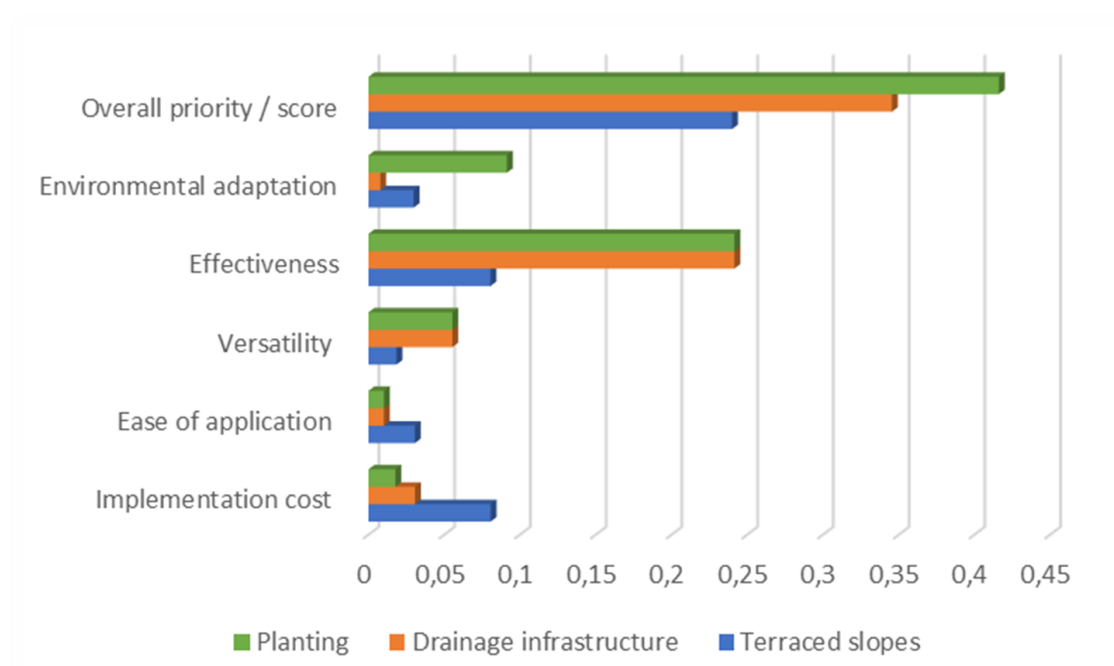


Figure 7: Evaluation priorities / scores

As can be easily seen from Figure 7, the Planting measure outperforms the other two in the overall evaluation of the evaluation criteria, although it clearly outperforms only one criterion, that of environmental adaptation. In terms of effectiveness and versatility, it ranks equal to Drainage and presents the highest implementation cost.

Sensitivity Analysis

All of the above applies in the case where there are no restrictions on the budget for the implementation of each measure. In the opposite case, that is, when financial resources are limited, then the same procedure is followed and its results are differentiated with regard to the comparative ranking of the criteria per pairs (Table 6) and finally, the optimal choice and the alternatives with their adequacy with respect to the evaluation criteria are shown in Table 7 and Figure 8.

Table 6: Pairwise comparison of the evaluation criteria (budget constraints)

Evaluation criteria	Implementation cost	Ease of application	Versatility	Effectiveness	Environmental adaptation	Priority
Implementation cost	1	7	5	1	5	0.384
Ease of application	1/7	1	1/3	1/7	1/3	0.041
Versatility	1/5	3	1	1/5	1/3	0.074
Effectiveness	5	7	5	1	5	0.384
Environmental adaptation	1/5	3	3	1/5	1	0.118

Table 7: Overall weights of preventive measures (budget constraints)

Preventive measure	Priority with respect to					Overall priority / score
	Implementation cost	Ease of application	Versatility	Effectiveness	Environmental adaptation	
Terraced slopes	0,24	0,0246	0,010582	0,054912	0,027258	0,357352 (~36%)
Drainage infrastructure	0,091392	0,0082	0,031746	0,164736	0,00708	0,303154 (~30%)
Planting	0,052608	0,0082	0,031746	0,164736	0,083544	0,340834 (~34%)

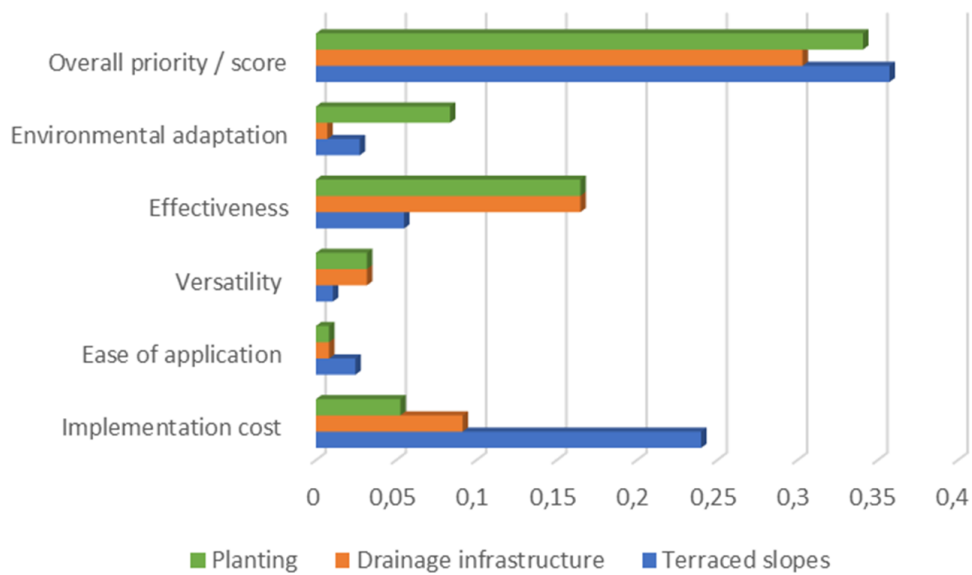


Figure 8: Evaluation priorities / scores (budget constraints)

In contrast to the results of the evaluation when there are no financial constraints, in the case where they exist, the most appropriate landslide prevention measure is demonstrated to be Terraced slopes, with Drainage coming close to the evaluation. Terraced slopes clearly excel in the criteria of implementation cost and ease of implementation, while in the rest it is far from the ideal choice.

As it is easily perceptible, the optimal result after conducting the proposed method, depends on the special characteristics and of each case and may differ from case to case. The authorized engineers of the road operator can use the proposed method as a tool to find the best alternative for the roadside slopes under inspection, so as to ensure slope stability and safety.

Conclusions

By applying the proposed method, a specific and overall picture of the options available is created. Thus, it is relatively easy to evaluate all alternatives for decision-making. Choosing the best measure is not a one-dimensional decision, but depends on many factors.

The proposed appraisal results in an analysis of preventive measures with regards to specific criteria and helps decision makers to conclude to the optimal choice according to their priorities and potentials. The optimal choice may differ according to special characteristics of each case examined.

The common practice adopted by road managers of consistently applying the same prevention measure over the years, disregarding any flaws or resource limitations, is likely to yield inaccurate results due to insufficient implementation processes related to the evaluation procedure. The purpose of this evaluation is to highlight the overall framework within which existing methods should be assessed and is intended to serve as a comprehensive tool for road professionals to conduct alternative assessment while also considering the resources available.

In conclusion, each measure presents its own benefits and drawbacks, which vary based on desired outcomes and financial constraints. To confidently choose the most appropriate one for landslide prevention, the approved personnel must thoughtfully consider the previously mentioned factors relevant to each situation evaluated.

Future research may be conducted in the frame of artificial intelligence integrated in the evaluation procedure, so as all special characteristics of each case will be considered thoroughly.

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