A cost-benefit analysis methodology for slope stabilization based on probabilistic stability analyses

Ellen Robson[1[0000-0002-5461-5479]], David Milledge[2 [0000-0003-4077-4898]], Stefano Utili[2 [0000-0003-3156-8013]] and Michael Bründl[3,4 [0000-0002-8826-1146]]

[1] Institute of Hazard, Risk and Resilience, Durham University, Durham, UK
[2] School of Engineering, Newcastle University, Newcastle upon Tyne, UK
[3] WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[4] Climate Change, Extremes and Natural Hazards in Alpine Regions Research Centre CERC, Davos Dorf, Switzerland
ellen.robson@durham.ac.uk

Abstract. It is best practice to evaluate the cost-efficiency of different road cut slope stabilization measures, prior to designing new cut slopes or stabilizing existing ones. This can be done by conducting a cost-analysis. Most cost-analysis methodologies require detailed data that is costly and time-consuming to collect (e.g., detailed historical data or data based on in-situ testing). We present a new cost-benefit analysis (CBA) methodology based on direct cost estimates that can be used to evaluate the cost-efficiency of different stabilization measures for a single cut slope that does not require expensive data. This CBA methodology incorporates a new method used to determine the frequency of a cut slope failure over a prescribed period, based on coupling a probabilistic stability analysis model with a hillslope-hydrological model (the hillslope-storage Boussinesq model). By determining the frequency of the cut slope failure, the cost of failure (remediation) over a prescribed period is established. The cost of failure for a particular cut slope design is combined with the initial upfront investment and running maintenance costs to determine the cost efficiency of implementing the stabilization measures over the entire cut slope lifetime. This methodology is suitable to compare the cost efficiency of many different stabilization designs.

Keywords: Cost-benefit analysis, Slope stability, Road cut slopes.

1 Introduction

Road construction often requires excavation resulting in cut slopes adjacent to roads, particularly in hilly regions. These cut slopes can be stabilized by implementing stabilization measures that include mechanical stabilization techniques (e.g. retaining walls, anchors and nails), bioengineering techniques, earthwork techniques and ground improvement techniques. The choice of stabilization method depends on slope characteristics (including the slope's geometry, geology, and hydrology), spatial constraints at the site, and the project budget and time constraints.

Cost analysis methodologies are used by consultants to optimize decision making in determining the most cost-efficient stabilization measures based on the aforementioned factors. This is common practice in High Income Countries (HICs), although in most countries there is no commonly accepted cost analysis framework meaning the level of model sophistication and assumptions adopted by consultants can vastly vary [1]. In low to lower-middle income countries (LIC/LMIC), costs analyses are less common due to a lack of resources and data. This can result in there being little understanding of what slope stability measures are most cost-efficient over time. For example, gabion and mortared masonry walls are ubiquitous throughout Nepal's road network, despite major differences in slope characteristics, as they are seen as low-cost measures. However, in many cases these fail during the annual monsoon season and have to be reconstructed and, therefore, could be less cost-efficient than alternative measures over time [2].

In the context of road infrastructure, as well as landslide and slope failure cost analysis studies in literature, cost analyses most commonly take the form of a cost-benefit analysis (CBA). In a CBA all the costs and benefits are monetized and compared against one another [3].

Landslide and slope failure CBA studies generally account for direct costs (associated with the direct damage, debris clearance and slope remediation) and/or indirect costs (associated with the knock-on effects of failure). Alternatively, Winter & Bromhead [4] categorize the economic impacts from a landslide into three categories: (1) direct economic impacts (direct costs of the clean-up and remediation); (2) direct consequential economic impacts (disruption to infrastructure and loss of utility); and (3) indirect consequential economic impact (disruption to transport-dependent activities).

To conduct a CBA to evaluate mitigative/stabilization measures, a method to establish the probability/frequency of slope failure must be established. These methods can be categorized into: (1) statistical analysis of a landslide database [5,6,7,8]; and/or (2) mechanistic slope stability analysis accounting for variable slope properties [9] and/or rainfall conditions [10].

While statistical models seem to be the most popular method to estimate the probability of failure in CBA studies, their predictive capability strongly depends on the similarity of the slope of interest to the set of slopes on which the model has been trained. Another pitfall of statistical models is the requirement for a large dataset which is particularly problematic in data scarce LIC/LMICs, as well as for road cut slope studies in general (larger landslide databases are more common as they can be established using remote sensing techniques). Conversely, mechanistic methods provide a better alternative to statistical (database driven) methods to estimate probability of failure for cut slopes as they enable: (1) a site-specific comparison of alternative stabilization methods with very precise user control over the specifics of the slope design; and (2) a comparison for the same forcing conditions. Both features are very difficult to achieve within a statistical framework because of the necessarily large pool of training data required to estimate the probabilities associated with each stabilization method. However, applications of mechanistic approaches are still surprisingly rare.

Holcombe et al. [10] employed a mechanistic model to demonstrate the value of implementing mitigative measures to protect a village in St. Lucia from a slope failure. A drawback of their method is that they did not account for ground material variability that can introduce considerable uncertainty in absolute estimates of slope failure probability. Probabilistic stability analyses can mitigate this uncertainty to some degree [9]. In addition, they use a 1-D Richard's Equation solver to model vertical infiltration which focuses on the cut slope and does not account for the influence of the surrounding topography on the groundwater regime. They also derive design storms from rainfall Intensity Duration Frequency (IDF) relationships which results in the shape of the storm time series being lost.

Here, we present a mechanistic CBA methodology to evaluate the cost efficiency of road cut slope stabilization measures accounting for direct costs. We monetize the efficiency of the stabilization measure in terms of the costs to rectify slope failure. The annual frequency of slope failure (F_f) is estimated using a recently proposed methodology from Robson et al. [11] which combines probabilistic stability analyses with the hillslope-storage Boussinesq (HSB) model to determine time varying seepage induced by rainfall over the lifetime of the road. In this model both the uncertainty of ground properties and realistic time varying phreatic surfaces within the slope (accounting for the hillslope groundwater regime) are accounted for. The outcome of the CBA is presented as an annual cost of the slope stabilization measure. This value can be used to objectively compare different slope stabilization measures.

2 Methodology

2.1 Cost analysis framework

We use a series of equations adapted from Bründl et al. [5] to determine the cost of the slope stabilization measure per annum (CE_n).

The initial investment (I_0) of the stabilization measure is determined by

$$I_0 = C(e) + C(s) + R_v(C(e) + C(s)) \quad (1)$$

where the cost of implementing the slope stabilization measure is partitioned into the cost of earthworks C(e) and the cost of building a structure C(s), and R_v is the value-added tax (VAT) which is country specific. C(e) can be estimated as the cost of excavation including the disposal of material (accounting for the geometry and type of material to be excavated). C(s) can be estimated as the costs incurred in building the structure (accounting for the geometry of the structure, the materials required, and the cost of labor/machinery to build that structure).

A cost comparison equation is used to equate the annual cost of construction (C_n):

$$C_n = C(m) + \frac{I_0 - C(r)}{n} + \frac{I_0 + C(r)}{2} R_d \quad (2)$$

where C(m) is the maintenance cost, R_d is the discount rate, C(r) is the remaining value of the structure, and n is the service life of the measure. The expression $I_0 -$ C(r))/n describes imputed depreciation, and the expression $R_d(I_0 + C(r))/2$ describes the average imputed interest. C(r) is only applicable to stabilization measures where the material can be used again post-failure (e.g. masonry walls). In those cases, C(r) is made equal to cost of the material that can be used again (otherwise C_n=0). The service life, n, is calculated using the method to estimate the frequency of slope failures outlined below (where n is the time until failure after implementation).

The overall cost per annum of a stabilization measure is equated as

$$CE_n = C_n + F_f(I_0 + C(c) + C(d)) \tag{3}$$

where C(c) is the cost of clearing the landslide debris and C(d) is the cost of dismantling the structure. C(c) can be estimated by working out the potential failure area based on the failure surface determined through a Limit Equilibrium Method (LEM) stability analysis. The area of landslide debris is then multiplied by the length of the cutting (parallel to the road) to determine debris volume. I_0 is included in this equation as the cost of reimplementing the stabilization measure after failure. C(d) accounts for the geometry of the structure and the cost of labor/machinery to deconstruct that structure. F_f is calculated using the method outlined below.

C(e), C(s), C(r) and C(d) are all specific to the geometry and materials of the slope stabilization measure implemented and should be based on a country-specific system of rate analysis.

2.2 Frequency of failure

We use a probabilistic method outlined in Robson et al. [11] to determine the F_f of a road cut slope with a stabilization measure implemented. This methodology does not require a database of failures, nor data from detailed site investigations, making it suitable for use in LIC/LMICs.

In the probabilistic method, a Monte Carlo simulation (MCS) is performed to capture variability in the slope geomaterial properties (characterized using Generalized-Hoek-Brown, G-H-B), with various phreatic surface levels imposed at a range of heights (NB: each phreatic level is associated to a different probability of occurrence in time). The stabilization measure is modelled in the stability analysis domain, and the stability analyses are performed using rigorous Morgenstern-Price (M-P) Limit Equilibrium Method (LEM) in Rocscience, Slide2. A sensitivity method is performed on the G-H-B parameters (range of values taken from literature) to determine the parameters that the model is most sensitive to and, therefore, those that should be varied in the MCS. The parameters to be varied as part of the MCS are then characterized according to a lognormal distribution, to derive realizations (number of realizations determined using a convergence analysis). Phreatic surfaces are generated using Finite Element (FE) steady state seepage analyses in Rocscience, Slide2 with a total head boundary condition of Z on the upslope boundary, carried out prior to the deterministic stability analyses.

The so-called hillslope-storage Bousinesq (HSB) equation of Troch et al. [12] (and outlined in Robson et al. [10]) is then solved in a finite difference scheme to generate a phreatic surface time series for the slope to account for hillslope hydrological conditions in response to rainfall (according to a rainfall time series). The HSB equation reformulates parts of the Boussinesq equation (the continuity and Darcy equations) in terms of the storage to reduce the 3-D flow problem to 1-D so that the runtime of the numerical solution is affordable. Given that hydraulic conductivity (k) is highly variable, the HSB equation is solved using multiple realizations of k (number of realizations determined using a convergence analysis) taken from a lognormal distribution of k characterized using a range of values from the literature.

By associating the phreatic surface level time series from the HSB model with those assessed in the MCS, Factor of Safety (FoS) time series for each G-H-B parameter realization and each k realization are generated. Each FoS time series is converted to a binary ‘failure' time series with failure for FoS<1 and stability for FoS>1. Each ‘failure' time series is worked through chronologically so that when failure occurs a failure count is iterated for that time series and then is censored for a number of remediation days (preventing further failures from being counted) to allow time for debris to be cleared and the cutting to be reinstated as it was (remediation time). The total number of landslides is then summed across all ‘failure' time series and normalized by the number of G-H-B parameter realizations and the number of k realizations to determine the overall number of landslides, which is then normalized to determine the annual frequency of failures (F_f).

The service life (n) can then be calculated as the total time of the study (total rainfall timeseries) divided by the F_f for the study period.

3 Results

This methodology can be employed to determine CE_n for a range of different slope stabilization measures options for a road cut slope. In doing so, the most cost-efficient slope stabilization measure (with the lowest CE_n) can be determined.

This methodology is employed by Robson et al [13] to compare the cost-efficiency of slope stabilization measures for a cut slope on a strategic road in Nepal.

4 Discussion

The outlined methodology only accounts for the direct costs associated with the stabilization of the road cut slope (initial construction, maintenance, and post-failure remediation). Including indirect costs could considerably increase overall cost of stabilization measures (reducing their cost-efficiency) which have high F_f and where landslide debris frequently blocks the road. However, it is important to note that cutting failures do not always result in road blockage as this depends on the volume of landslide debris and thus the extent of the failure surface [14]. Also, indirect costs are of more uncertain determination. Indirect costs could be accounted for by incorporating methods outlined by Hearn et al. [7] (who account for the cost of vehicle being stuck in traffic), MacLeod et al. [15] (who account for the cost of detours) or Winter [16] (who assign direct, direct consequential and indirect consequential economic impacts to landslides).

5 Conclusion

This paper presents a new cost-benefit analysis methodology that can be used to evaluate the cost-efficiency of road cut slope stabilization measures based on a mechanistic probabilistic approach to derive a frequency of failure. The model output is a cost per annum which accounts for the direct costs of initial investment, maintenance, and remediating slope failure. The cost of remediating slope failure depends on the frequency of slope failure which is estimated using a new methodology outlined by Robson et al [11]. This model accounts for geomaterial variability and hillslope hydrology. Given that this probabilistic method does not require a database of slope failures, nor costly input data, it is suitable for use in a LIC/LMIC setting.

References

1. Vagdatli, T., Petroutsatou, K: Modelling approaches of life cycle cost–benefit analysis of road infrastructure: a critical review and future directions. Buildings 13(1), 94 (2022).
2. Robson, E., Utili, S., Milledge, D: Road slope stabilisation in Nepal: stakeholder perspectives. SCG-XIII INTERNATIONAL SYMPOSIUM ON LANDSLIDES 2020, Cartagena (2021).
3. Browne, D., Ryan, L: Comparative Analysis of Evaluation Techniques for Transport Policies. Environ. Impact Assess. Rev 31, 226–233 (2011).
4. Winter, M. G., Bromhead, E. N: Landslide risk: some issues that determine societal acceptance. Natural Hazards 62(2), 169-187 (2012)
5. Bründl, M., Romang, H. E., Bischof, N., Rheinberger, C. M: The risk concept and its application in natural hazard risk management in Switzerland. Natural Hazards and Earth System Sciences 9(3):801–813 (2009).
6. Grima, N., Edwards, D., Edwards, F., Petley, D., Fisher, B: Landslides in the Andes: Forests can provide cost-effective landslide regulation services. Science of the total environment 25(745), 141128 (2020).
7. Hearn, G. J., Kerridge, M. S. P., Pongpanya, P: Landslide costs on the national road network of Laos, with some regional implications. Quarterly Journal of Engineering Geology and Hydrogeology 54(4), (2021).
8. Klose, M., Damm, B., Terhorst, B: Landslide cost modeling for transportation infrastructures: a methodological approach. Landslides 12(2), 321–334 (2015)
9. Li, A. J., Cassidy, M. J., Wang, Y., Merifield, R. S., Lyamin, A. V: Parametric Monte Carlo studies of rock slopes based on the Hoek–Brown failure criterion. Computers and Geotechnics 45, 11–18 (2012)
10. Holcombe, E., Smith, S., Wright, E., Anderson, M. G: An integrated approach for evaluating the effectiveness of landslide risk reduction in unplanned communities in the Caribbean. Natural Hazards 61(2), 351–385 (2012)
11. Robson, E., Milledge, D., Utili, S., Dattola, G: A computationally efficient method to determine the probability of rainfall triggered cut slope failure accounting for upslope hydrological conditions. Rock Mechanics and Rock Engineering. (In press).
12. Troch, P. A., Paniconi, C., van Loon, E. E.: Hillslope-storage Boussinesq model for subsurface flow and variable source areas along complex hillslopes: 1. Formulation and characteristic response. Water Resources Research 39(11) (2003).

13. Robson E., Milledge D., Utili S., Bründl, M.: Cost-benefit methodology for road slope stabilisation. Geotechnique (forthcoming)
14. Hearn, G: Slope engineering for mountain roads. 24. Geological Society of London, London (2011)
15. MacLeod, A., Hofmeister, R. J., Wang, Y., Burns, S: Landslide indirect losses: methods and case studies from Oregon. Open File Report O-05-X. Oregon Department of Geology and Mineral Industries (2005)
16. Winter, M. G., Shearer, B., Palmer, D., Peeling, D., Peeling, J., Harmer, C., Sharpe, J: Assessment of the economic impacts of landslides and other climate-driven events. TRL (2018)