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Analysing the effect of rainfall on railway embankments using fragility curves

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Abstract

Many railway embankments across Europe were constructed over 150 years ago. These embankments were not subject to rigorous design practice but instead were crudely constructed using end tipping techniques. As a result, the majority of these embankments are overly steep and far in excess of the design angles recommended in Eurocode 7. Over recent years, increased incidence of failure has been witnessed on these slopes following periods of prolonged or intense precipitation. This paper develops fragility curves to investigate how sensitive these steep slopes are to shallow translational failure when subjected to prolonged or abnormally intense rainfall. Rainfall intensity and condition are both considered for a range of slope angles. The significance of the findings are discussed in the context of transport slope asset management and risk assessment. The approach is a logical expansion on probabilistic slope stability analysis and could be used to interpret how vulnerable the transport network is to changing climatic condition.

Keywords: Slope Stability; Rainfall-Induced Failure; Embankments; Vulnerability; Probability of Failure

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Nomenclature

FOS Factor of Safety
COV Coefficient of variation
c' Effective cohesion [kPa]
ϕ' Friction angle of soil [°]
u Porewater pressure [kPa]
α Inclination of slice base [°]
β Reliability Index
g(X) Performance function
h Wetting front depth [m]
H Total head [m]
Kx Hydraulic conductivity in x (horizontal) direction [ms^{-1}]
Ky Hydraulic conductivity in the y (vertical) direction [ms^{-1}]
Q Applied boundary flux [ms^{-1}]
θ Volumetric water content
t Time [s]
τ Unsaturated shear strength of the soil [kPa]
σ_n Total normal stress, u_a is the pore-air pressure [kPa]
u_w Positive pore water pressure [kPa]
$u_a - u_w$ The matric suction [kPa]
ϕ^b The angle which describes the rate of increase in shear strength due to matric suction. [°]
α Slope angle [°]
γ Soil unit weight [kNm^{-2}]
X A vector of the different random variables (x_i) represented in the slope
E[] Mean
σ[] Standard deviation.
R_i Rainfall intensity [mmh^{-1}]
p_f Probability of failure
SEEP/W finite element flow solver

1. Introduction

Shallow translational slope failures are a common occurrence on railways worldwide. Typically such failures are observed on steep embankment sections following periods of prolonged or abnormally intense rainfall (Jennings and Muldoon 2001; Martinovic K. et al. 2016; Tang et al. 2011). This is particularly problematic for transport networks with large lengths of aged embankments such as Ireland and the United Kingdom. Where the vast majority of aged embankments were built during the mid-1800s. They were constructed by end tipping small volumes of soil from horse-drawn carts before compacting and shaping the material using hand tools. In Ireland the majority of such embankments were constructed out of Glacial Till, a material which can sustain substantial negative pore pressures, thus allowing the construction of slopes with inclinations in excess of their natural angle of repose (Gavin et al. 2004). Unfortunately, as these slopes rely on soil suction (-ve pore pressure) for stability it makes them more susceptible to rainfall-induced shallow failures. Years with above average rainfall, such as 2012, have proved this, with many failures recorded on overly steep legacy transport infrastructure relative to their modern equivalents. Whilst a number of reasons could contribute to this such as poor maintenance and an absence of adequate drainage, the main mechanism behind these failures remains reduction in the negative pressure head within the near-surface soils following rainfall infiltration.

All soils which lie above the natural groundwater level have a negative pore pressure head. This pressure head develops as a result of capillary action, caused by the interaction of occluded water and air within the soil pore space (Ridley et al. 2004). The magnitude of this pressure head is dependent on a number of factors namely; the size of the respective soil particles, the clay content of the soil, the water content of the soil, and the presence of significant macro-structural anomalies such as desiccation cracks, root networks, and animal burrows (Fredlund and Rahardjo 1993). In dry weather, the water content within the soil reduces by first draining water from the macropores, before draining from the micropores. This preferential flow is due to the higher energy cost associated with removing water from micropores as the capillary effects are greater there. These capillary effects exert a significant pull on adjacent soil particles creating a tensile force within the soil. Which in turn, increases the cohesiveness of the soil, adding shear strength to the slope. During periods of rainfall, water infiltrates into the slope, creating a wetting front which percolates downward into the soil filling available pore space as it advances, thereby removing some or all (depending on the severity of the rainfall event) of the additional stability benefit obtained from capillary effects (Reale et al. 2012; Tang et al. 2011). If this wetting front progresses downward to some critical depth, the combination of reduced soil shear strength and the related increase in soil unit weight will lead to equilibrium being overcome and subsequent failure.

As slopes constructed at angles in excess of their respective angles of repose rely on negative pore water pressures for stability, they are more susceptible to changes in climatic condition. The economic costs associated with replacing and upgrading this infrastructure is substantial and railway operators have limited annual access to funds for upgrading slope infrastructure. However, most operators are keen to move away from a reactive maintenance model, which leaves them open to a greater risk of catastrophic failure occurring. Instead, infrastructure managers are moving towards a more proactive maintenance model, where degradation effects are monitored and suspect infrastructure is identified and remediated/replaced before becoming critical. This process is occurring across the Civil Engineering domain with infrastructure managers concerned with the long-term viability of bridges (O'Connor and Enevoldsen 2007; Prendergast et al. 2016; Prendergast and Gavin 2016; Reale and O'Connor 2012), slopes (Hicks and Spencer 2010; Power et al. 2016), tunnels , and other infrastructure. Analysing capacity and consequence using a probabilistic framework, helps infrastructure owners understand the criticality of each asset. Allowing them to invest money in a prudent and consistent manner, designed to elicit the greatest return on investment (Vardon 2015).

This paper describes the development of a series of fragility curves looking at the effect rainfall has on the stability of steep Irish Glacial Till embankments. The curves are a natural progression from standard slope reliability analysis, in that they follow a similar methodology but examine how vulnerable the slope is to variation in rainfall. The curves are developed in a manner consistent with current risk practice allowing the results to be incorporated into life cycle analysis tools, decision support tools, and cost-benefit models enabling infrastructure managers to extract all necessary information. Probabilistic methods are ideally suited to the analysis of rainfall-induced failures as both the load (disturbing force) and the resistance vary temporally as a result of climate (Babu and Murthy 2005).

2. Development of Fragility Curves

2.1. Formulation of Limit State Equation and Infiltration analysis

Slope stability was classically assessed using a factor of safety approach where the capacity of the slope was defined as the ratio of the resistance moment (Capacity) to the overturning moment (Demand) along a potential slip surface, see Equation 1.

$$FOS = \frac{Capacity}{Demand} \tag{1}$$

Fredlund et al. (1978) expanded the Mohr-Coulomb soil shear strength model to incorporate the effect of matric suction, this updated shear strength model can be described by Equation 2.

$$\tau = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \tag{2}$$

Incorporating this expanded Mohr-Coulomb equation into an infinite slope model which assumes that the failure depth and the wetting front depth are coincident, see Fig 1, the Factor of Safety (FOS) of the slope can be obtained from Equation 3.

$$\mathrm{FOS} = \frac{c' + (u_a - u_w)\tan\phi^b + \gamma h \cos^2\alpha \tan\phi'}{\gamma h \sin\alpha \cos\alpha} \tag{3}$$

The seepage of rainwater into a slope and subsequent wetting front position is modelled using Richard's equation (Richards 1931) for unsaturated flow, see Equation 4.

$$\frac{\delta}{\delta x}\left(k_x \frac{\delta H}{\delta x}\right) + \frac{\delta}{\delta y}\left(k_y \frac{\delta H}{\delta y}\right) + Q = \frac{\delta \theta}{\delta t} \quad (4)$$

This method has been applied in this paper to calculate how soil suction changes over time within the slope as rainwater infiltrates.

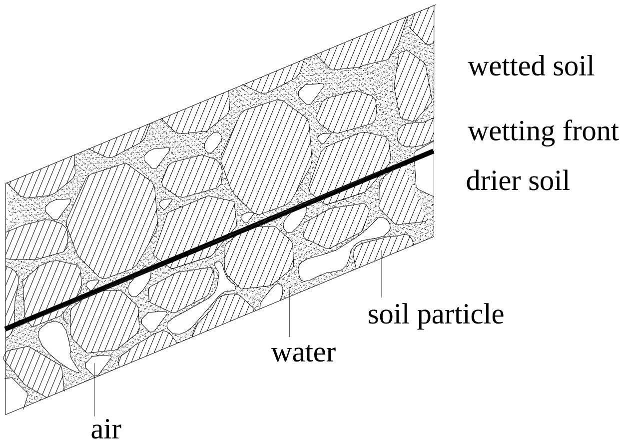

Fig 1 Development of the wetting front in unsaturated soil

2.2. Probabilistic methods

Over recent decades probabilistic methods have become increasingly common across many facets of Transport Engineering. With slope stability receiving particular attention (Cheng et al. 2015; Liang et al. 1999; Reale et al. 2015; Xu and Low 2006). This is due to researchers recognizing the inadequacy of deterministic design in light of the significant uncertainties associated with site investigation (Phoon and Kulhawy 1999), slip surface location (Reale et al. 2016b), climate (Babu and Murthy 2005) and of course spatial variation (De Gast et al. 2017; Hicks et al. 2014; Prendergast et al. 2017; Reale et al. 2017). Probabilistic or reliability analyses allow designers to account for uncertainty by assigning probabilistic distributions to input parameters, subsequent stability analyses, therefore, consider the full range of values a parameter is likely to have instead of assuming discrete point values. Thereby offering a more meaningful rational interpretation of slope safety over traditional deterministic design which assumes fixed point values with no variation (Reale et al. 2016a; b). The performance function g(X) of a slope can be expressed as the difference between a slopes capacity (C) and demand (D) or the FOS – 1, see Equation 5.

$$g(X) = (C - D)\begin{cases} > 0, safe\ state \\ = 0, limit\ state \\ < 0, failure\ state \end{cases} \quad (5)$$

$$g(X) = g(x_1, x_2, \dots, x_n) for\ i = 1\ to\ n$$

where X is a vector of the different random variables (x_i) represented in the slope. Safety in the context of a probabilistic analysis is typically expressed in terms of a reliability index, β, and a probability of failure, p_f. The probability of failure (p_f) can be defined as the probability at which the performance function is less than zero, see Equation 6.

$$P_f = P[g(X) \leq 0] \quad (6)$$

While the reliability index (β) is the distance in standard deviations from the mean of the performance function to the failure zone Equation 5, this can be seen graphically in **Figure 2**.

$$\beta = \frac{E[g(X)]}{\sigma[g(X)]} \tag{7}$$

To analyse the slope probabilistically the performance function of the slope is formulated as in Equation 8.

$$g(X) = FOS - 1 \tag{8}$$

Where the FOS is the factor of safety is defined by the relevant limit state equation, in this case, Equation 3.

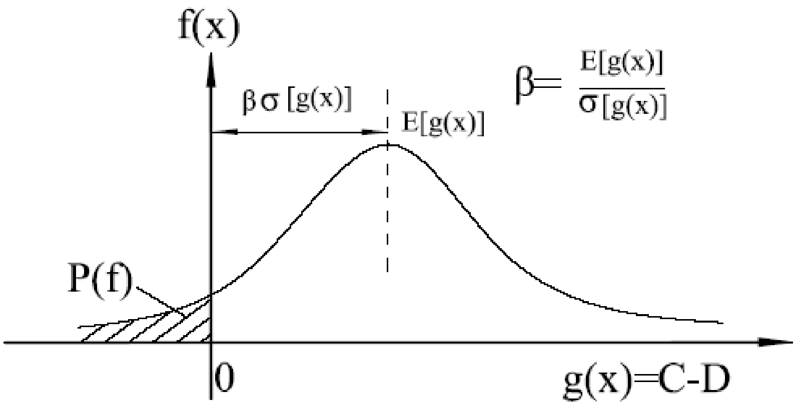

Figure 2 The relationship between the reliability index and the probability of failure

There are at present a number of means of performing a probabilistic analysis of Equation 8. These can be separated into two distinct groups approximate methods such as FOSM (first-order second moment) etc. and simulation methods such as Monte Carlo. This paper utilizes an approximate method namely first-order reliability method more commonly known as FORM. This approach is discussed below.

2.3. First Order Reliability Methods Hasofer Lind

Hasofer & Lind (1974) developed a method which assumes a first order tangent to the limit state function at the design point (i.e. the location on the performance function for which g(X) = 0). This method gives an exact solution for linear performance functions and a close approximation for nonlinear functions. This method requires all computation to be carried out in the standard normal space. Therefore the vector of random variables (X) needs to be transformed into a vector of standardised normal uncorrelated variables ($\bar{X}$) prior to minimisation. Equation 9 can be used to transform random variables into the standard normal space.

$$\bar{X}_i = \frac{x_i - \mu_{x_i}}{\sigma_{x_i}} \quad for \;\; i = [1,2,\dots,n] \tag{9}$$

In this space, the reliability index can be calculated by Equation 10.

$$\beta = \min_{\bar{X}\epsilon\psi}\{\bar{X}\bar{X}^T\}^{1/2} \tag{10}$$

Where the limit state surface Ψ is defined by $g(\bar{X}) = 0$.

2.4. Intensity Measures

The fragility curves developed in this study express the probability of reaching or exceeding failure for a given intensity measure, rainfall loading. Naturally, for a different rainfall loading scenario, the probability of failure will change. Rainfall duration is considered on the x-axis of the fragility curves as opposed to total rainfall as the same total rainfall value can result from many different combinations of rainfall intensities and durations, and the resultant infiltration will differ across these combinations (Gavin and Xue 2008). The initial fragility curves developed in this study assume a constant rainfall intensity of 5 mm/h. Total rainfall applied be acquired by simply multiplying the rainfall intensity and rainfall duration at the point of interest. The fragility curves are developed by calculating the probability that the reliability index from slope stability calculations will be equal to or less than zero for a range of rainfall durations. The geotechnical parameters assumed are shown in Table 1.

Table 1: Glacial till geotechnical parameters used in the development of fragility curves

	Unit weight γ [kN/m^3]	Angle of internal friction φ' [°]	φ^b [°]*	Effective cohesion c' [kN/m^2]	Saturated permeability Ks [m/s]	Initial suction [kN/m^2]	Residual suction [kN/m^2]
Mean value	19	36	36	1	1 x 10^{-6}	20	3
COV	0.02	0.1	0.1	0.2	-	-	0.1

** angle indicating the rate of increase of the shear strength due to matric suction*

3. Results and Discussion

Using the methodology outlined above fragility curves were developed assuming that a reliability index less than unity constituted a failure. Irish glacial till was the material chosen to illustrate the development of rainfall-induced shallow landslide fragility curves as it accounts for approximately 50% of the surface soil deposits in Ireland (Fealy et al. 2009). Hence, much of the Irish Rail cuttings and embankments network is constructed of this material. However, it is important to note that these curves can be generated for any soil type and for this research to be of practical benefit to infrastructure managers, these curves would need to be developed on a regional basis taking into account likely soil material parameters, soil types, variation, and of course climate. The example curves depicted here were generated using the values outlined in Table 1, together with wetting front depths and corresponding rainfall durations, obtained from a SEEP/W rainfall infiltration analysis. A FORM probabilistic slope stability analysis was performed on the limit state function presented in Equation 8. The resulting fragility curves are presented in Figure 3. The developed curves assume a constant rainfall intensity of 5 mm/hr, which corresponds with the red colour in the "traffic light" weather warning system employed by the Irish weather forecasting service Met Eireann. We can clearly see that the steepness of the slope has a huge effect on its ability

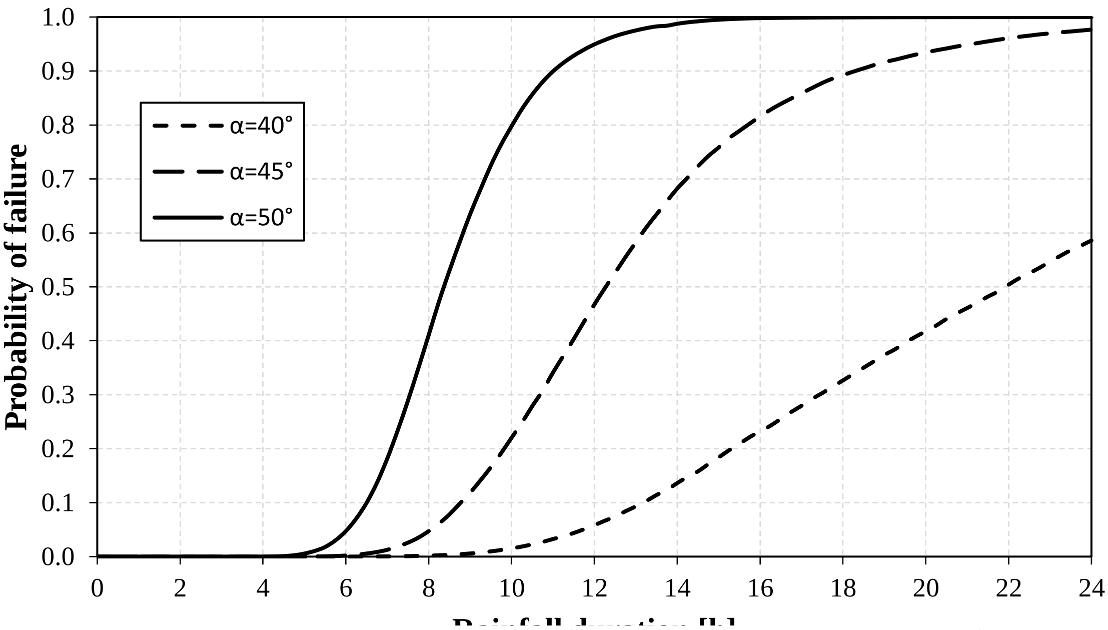

Figure 3 Fragility curves showing the vulnerability of steep Irish Glacial till slopes to prolonged rainfall

to withstand prolonged rainfall. This effect becomes more pronounced with increasing slope angle, as can be seen by the increased steepness of the fragility curves.

Figure 4 explores the effect rainfall intensity has on the probability of failure for a 45^0 slope. Here we can clearly see if the rainfall intensity is reduced the wetting front takes considerably longer to develop. However, if the rainfall intensity is increased further there is no further increase in the probability of failure (at least without considering alternative failure mechanisms) as the slope is at infiltration capacity. Therefore further increase in rainfall will result in greater rainfall runoff.

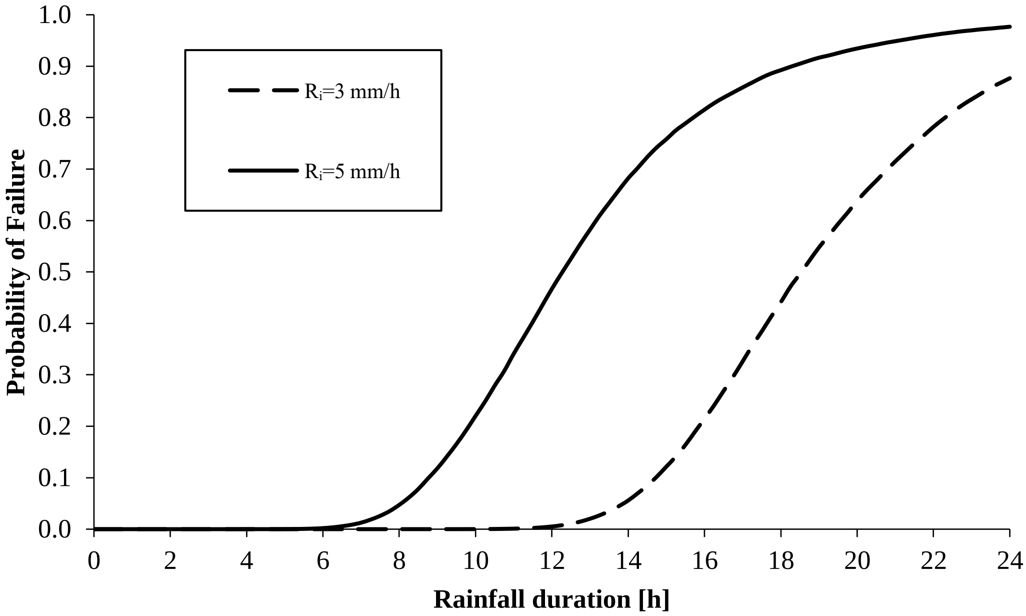

Figure 4 Effect of rainfall intensity on the probability of failure

Given that the saturated permeability of the soil is one of the most difficult parameters to ascertain accurately, a high level of uncertainty surrounds it. The influence of this parameter on the shape of the fragility curves is considered in **Figure 5**. Values for saturated permeability were taken as 50% higher and 50 % lower than the initial case study value, amounting to 1.5x10-6 m/s and 5x10-7 m/s respectively were considered. The values are seen to have a significant impact on the rainfall duration required for a failure to occur. A high permeability will naturally drain faster and as a result, will need a greater sustained rainfall intensity to maintain wetting front development, however, if the rainfall intensity is sufficient the wetting front can reach critical depth quickly. Conversely, for a soil low permeability, the rainfall intensity is less important as even moderate rainfall will quickly exceed the infiltration capacity. In such a case the duration of the rainfall event will take prominence with sustained rainfall of low intensity more likely to cause failure.

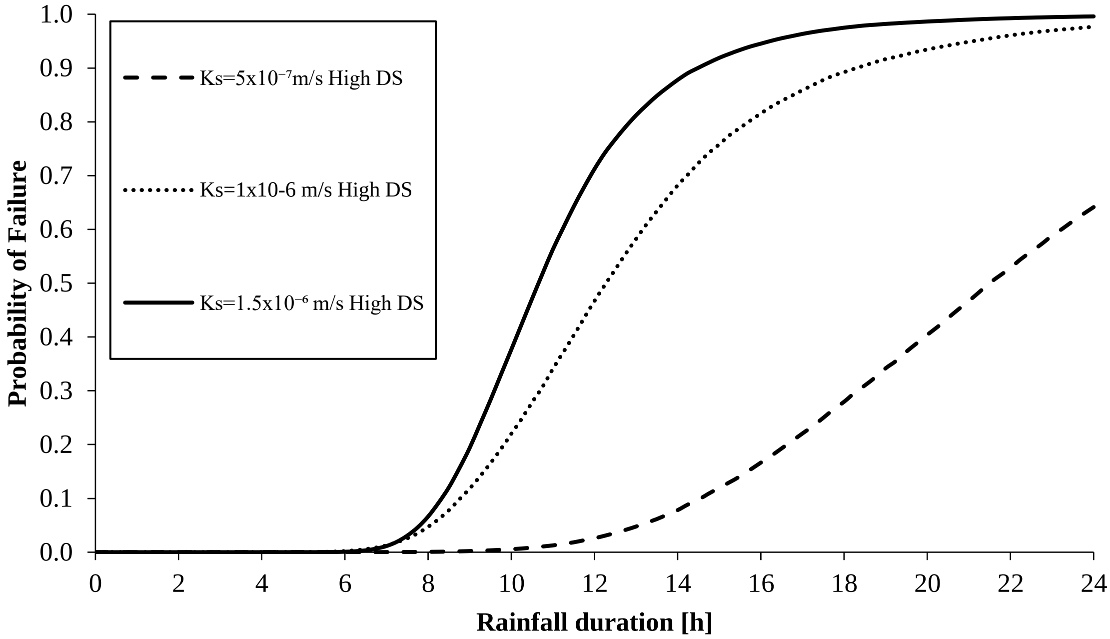

Figure 5 The effect of saturated permeability on the probability of failure, under prolonged rainfall

4. Conclusions

This paper outlines a methodology for developing fragility curves for unsaturated soil slopes subject to rainfall-induced shallow landslides and presented some initial results on the subject. The loading event or intensity measure used is the product of rainfall intensity and duration, while the assumed failure mechanism is that of a translational shallow slide occurring parallel to the slope surface. As the result of shear strength reduction caused by infiltrating rainwater lessening the impact of soil suction on stability. The fragility curves are modelled using a combined FORM/SEEP W analysis to determine the change in reliability index with time. The presented curves monitor the change in slope capacity with rainfall and examine how slope angle, saturated permeability, and rainfall intensity effect stability under prolonged rainfall. The saturated permeability was shown to have a large impact on slope stability under prolonged rainfall, while this is to be expected it is somewhat problematic as soil saturated permeability is notoriously difficult to measure accurately and can vary significantly across a site. Glacial Till embankments are shown to be increasingly susceptible to rainfall-induced failure as their angle of inclination increases. If developed regionally these curves could be used by infrastructure managers in conjunction with detailed weather forecasts to justify reducing speed or closing services when the risk of catastrophic failure is judged to be outside of allowable levels. The number of curves needed to accurately encapsulate a transport network will depend on the local geology and how it varies across the network in question.

Future work will analyse how sensitive the approach is to parameter variability as well as validate and verify the approach using data from real life landslides events to achieve this goal.

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