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The influence of slope geology on landslide occurrence during extreme rainfall

L'influence de la géologie de la pente sur glissement de terrain lors de précipitations extrêmes

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ABSTRACT Extreme rainfall events, seasonal weather extremes and long term climate change present a threat to the stability of natural and engineered slopes by altering slope hydrology and shear strength beyond recent historical values.

The temporal and spatial fluctuation of slope wetting and drying in response to weather event sequences can be represented using a surface water balance approach of rainfall infiltration and potential evapotranspiration, such as a soil moisture deficit calculation (SMD). This provides an opportunity to address the regional susceptibility of slopes to become unstable when exposed to adverse weather event sequences. However, case studies have shown that site specific characterisation of foundation geology (e.g. permeability and shear strength) is required to assess the vulnerability of specific slopes to pore water pressure fluctuations and slope failure during extreme weather events.

The relationship between underlying geology and landslide incidence during extreme weather extremes is illustrated by comparing long term weather data, soil moisture deficit calculations and geological information using a database of over 400 UK landslide events that occurred between 2004 and 2014.

RÉSUMÉ Des événements de précipitations extrêmes, des extrêmes climatiques saisonniers et les changements climatiques à long terme présentent une menace pour la stabilité des pentes naturelles et du génie en modifiant l'hydrologie de la pente et la résistance au cisaillement au-delà des valeurs historiques.

La fluctuation temporelle et spatiale de mouillage de la pente et le séchage en réponse aux conditions séquences d'événements peut être représentée à l'aide d'une approche de l'infiltration des précipitations et l'évapotranspiration potentielle, l'équilibre des eaux de surface telles que le calcul du déficit de l'humidité du sol (SMD). Ceci fournit une occasion d'aborder la sensibilité régionale de pistes à devenir instable lorsqu'il est exposé à des séquences d'événements indésirables météo. Cependant, des études de cas ont montré que la caractérisation du site spécifique de la fondation de la géologie (par exemple, la perméabilité et la résistance au cisaillement) est nécessaire pour évaluer la vulnérabilité des pistes spécifiques à pores fluctuations de pression de l'eau et des ruptures de pente lors d'événements météorologiques extrêmes.

La relation entre la géologie sous-jacente et de l'incidence des glissements de terrain au cours des extrêmes météorologiques extrêmes est illustré en comparant les données à long terme de météo, calcul du déficit d'humidité du sol et des données géologiques en utilisant une base de données de plus de 400 événements au Royaume-Uni de glissements de terrain qui ont eu lieu entre 2004 et 2014.

1 INTRODUCTION

Landslides have a significant socio-economic impact. This includes causing damage to property, disruption to transport infrastructure and posing a threat to human life (Petley et al. 2005). The assessment and mitigation of landslide hazards requires an understanding of triggering factors and how these may vary spatially (e.g. due to local geology) or temporally (e.g. in response to extreme weather or changing climate patterns).

Hydrological triggering is considered to be a principal landslide initiation mechanism (Van Asch et al. 1999). Increased pore water pressures act to reduce the shear strength of soils, triggering the failure of marginally stable slopes.

By examining historical landslide records and comparing them with climate data it is possible to identify meteorological threshold values for periods of increased slope instability. A common approach is to estimate a meteorological threshold based on rainfall intensity and duration (Guzzetti et al. 2008). However, the rate and quantity of surface water infiltration (causing increased pore water pressures) is influenced by the geological conditions (e.g. soil type, saturation and permeability) and the antecedent weather conditions (Zhang et al. 2011). This can affect the time of landslide occurrence and the type of landslide failure mechanism (Leroueil 2001).

Soil water balance approaches such as the calculation of soil moisture deficit (SMD) can be used to consider the long term influence of rainfall, runoff and evapotranspiration on surface water infiltration (Blight 2003) and to assess trends in landslide triggering. For example, Hutchinson (1995, cited Leroueil (2001)) showed that landslides in the London Clay cliffs at Southend-on-Sea occurred when SMD was less than around 10mm between 1967 and 1976. A similar relationship between landslide occurrence and periods of low SMD has been shown by Kovacevic et al. (2001, cited Macdonald et al. 2012), Ridley (2004) and Wilson (2003).

Network Rail has used SMD to predict periods of likely slope instability and identify risk areas within the rail network since 2000 (Birch & Dewar 2002). The Network Rail threshold considers average monthly rainfall above 175% of the historical long term average during periods of SMD close to zero (Winter et al. 2006). It has proved to be a valuable tool as part of an effective early warning system (Goldfingle 2010).

An evaluation of existing landslide triggering thresholds and large scale trends requires records of the type, time and location of landslide events over a range of long term weather conditions including extreme events and from a range of geological areas. With the integration of news and media reports into landslide records, the British Geological Survey (BGS) has collated a landslide database of over 400 landslide events from across the UK between 2004 and 2014.

The aims of this paper are to consider the influence of long term weather, extreme rainfall and the underlying slope geology on the type and time of landslide occurrence, for comparison with existing landslide trigger thresholds. The type, time and location of over 400 landslide events recorded by the BGS over ten years are compared with rainfall data, geological permeability indices and the calculated soil moisture deficit.

2 METHOD

Met Office (2014) weather data for England and for Scotland was used to plot daily rainfall and to calculate the long term soil moisture deficit (SMD) for the period 2004 to 2014. This was compared with the type and time of landslide occurrence recorded within the BGS landslide database. Landslide location records were compared with geological maps of the superficial and bedrock geology. This was used to identify geological features such as low permeability soils or the presence of underdrainage by permeable bedrock which might influence groundwater response to extreme weather (Briggs et al. 2013).

2.1 Soil Moisture Deficit

Soil moisture deficit is a water balance calculation of the volume of water required to keep a soil at its field capacity (the equilibrium moisture content within a soil allowed to drain freely under gravity). Zero SMD indicates a soil at field capacity, where there is potential for positive pore water pressures to be generated in saturated soil.

SMD is calculated by accounting for the daily balance of rainfall, runoff, and the evapotranspiration of water from the soil (Clarke & Smethurst 2010). Potential evapotranspiration was estimated using the Penman-Monteith equation (FAO-56 method (Zotarelli et al. 2010). Daily SMD was calculated for both central Scotland and central England using daily data from Met Office weather stations at Strathspey and Northampton respectively. SMD was not calculated at individual sites, therefore neglecting the influence of localised weather and vegetation conditions.

2.2 BGS Landslide Database

The British Geological Society first created a landslide database in the 1980's and the current version now contains over 17,000 events (Pennington et al. 2014). However, it is only since 2004 and the gradual integration of media reports into the system, that most events are recorded with accurate temporal data (i.e. a precise date 'stamp' of occurrence). Since 2004, over 400 dated landslide records have been added to the database (coastal landslides have been excluded from the scope of this study). Within the database each event is related to information including the type, time and location of the landslide.

Figure 1 shows the distribution of the events within the database according to the BGS landslide type classification described in Foster et al. (2012). Slope failures are the most numerous landslide failure type within the database. This classification contains landslides on man-made slopes affecting transport infrastructure (e.g. road and rail embankments and cuttings). Many of these records were reported via social media and the exact nature of the landslide failure is not known.

Since 2012, social media has been incorporated into the search system used to populate the database. This has resulted in an increased number of recorded events in the period 2012-2014, as many of the smaller, low impact events which might have previously gone unreported are now detected. The use of media sources does not provide a comprehensive record of all events but it does provide a cost-efficient way to gain an understanding of landslide trends.

Pennington et al. (2014) explored the relationship between antecedent rainfall and landslides in south-west England using the BGS landslide database. Three different types of landslide recorded in the BGS database (falls, slope failures, and translational/planar slides) were examined. Falls were found to correlate with longer term antecedent rainfall (60 days), whereas planar slides and slope failures correlated with shorter-term antecedent rainfall (between 7 and 30 days, and between 1 and 7 days respectively). However, Pennington et al. (2014) noted that these conclusions were based on a limited number of observations in a regional study.

2.3 Geological Maps

Landslide records were overlaid on superficial and bedrock geology maps (1:50,000 scale) using GIS software (ArcGIS). This associated each landslide record with a bedrock and superficial geology (Figure 2), giving an indication of geological features which might influence local hydrogeology in response to weather.

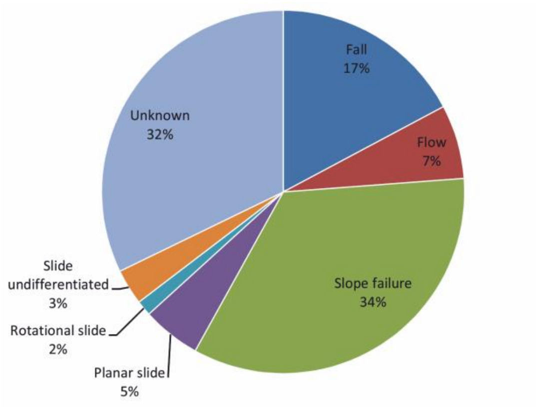

Figure 1. Landslide failure type division of 441 records (2004-2014) within the BGS landslide database.

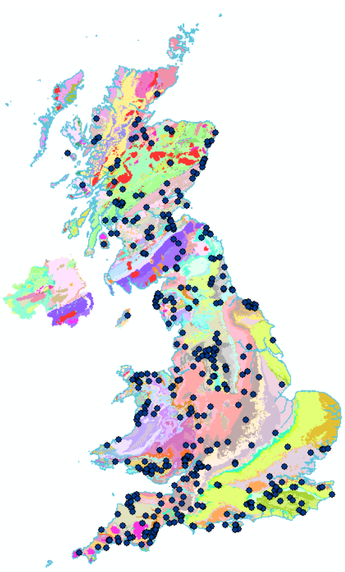

Figure 2. BGS landslide database records (2004-2014) (excluding coastal events) overlaid on a map of UK bedrock geology (© NERC 2014).

2.4 Permeability Classes

The permeability of the superficial and bedrock geology influences the ability of rainfall to infiltrate and to drain from slopes during periods of extreme rainfall (Briggs et al. 2013). Broad permeability classes (high, moderate and low) (Table 1) were used to indicate the influence of superficial and bedrock geology on local hydrogeology at the landslide locations. The permeability classes were based on the BGS permeability indices (Lewis et al. 2006) categorising every lithology within the Digital Geological Map of Great Britain (DiGMapGB-50). Although this qualitative ranking of soil and rock permeability does not allow a great deal nuance, it allows a simplified examination of its influence on landslide occurrence.

Table 1 – BGS landslide database events (2004-2014) categorised by BGS permeability class.

Permeability Class	England/Wales	Scotland
Bedrock Geology		
Low permeability	6	27
Moderate permeability	214	43
High permeability	94	37
Unknown	20	0
Superficial Geology		
Low permeability	6	12
Moderate permeability	82	48
High permeability	26	25
Unknown	220	22

3 RESULTS AND DISCUSSION

The rainfall data, soil moisture deficit and permeability classes were used to explore trends within the BGS landslide database. The following questions were considered:

Landslides and specifically slope failures are associated with low SMD (Hutchinson 1995, cited Leroueil 2001; Ridley 2004)
Figure 3 shows that around 66% of landslide events occurred when SMD was at, or very close to zero. If the failures are sorted by type, this relationship becomes much more pronounced. Approximately 90% of slope failures occurred when SMD was less than 1mm. Flow and fall type failures occurred less frequently during periods of low SMD. Cumulative rainfall analysis showed that slope failures are triggered by lesser antecedent rainfall than flow or fall type failures (Pennington et al. 2014). Slope failures are more closely linked to prolonged, low intensity surface water infiltration than fall or flow type failures.

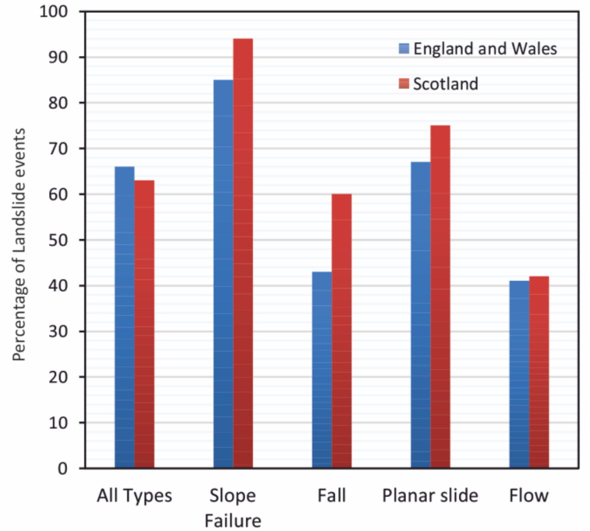

Figure 3 – Landslide events by failure type during periods of low (<1mm) Soil Moisture Deficit (2004-2014).

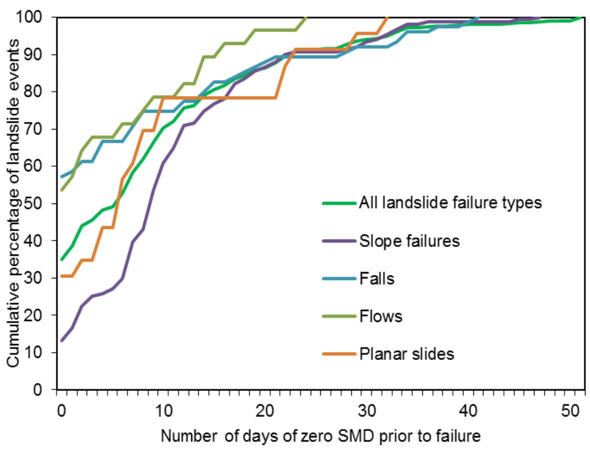

Figure 4 – A comparison of the cumulative percentage of landslide events and the number of days of zero SMD prior to failure, sorted by failure type.

A rapid reduction in SMD (e.g.. intensive rainfall following a prolonged dry period) is associated with earthwork slope failures (Macdonald et al. 2012)
No correlation was observed between slope failures (or any type of failure) and a large (> 25mm) reduction in SMD during the week prior to failure.

Landslides are associated with intensive rainfall on the day of failure (Guzzetti et al. 2008)
The majority of the events were triggered by daily rainfall of less than 10mm. Daily rainfall alone was not a good indicator of landslide occurrence.

Landslides and specifically slope failures are associated with above-average rainfall during periods of low SMD (Birch & Dewar 2002)
Figure 4 shows that slope failures generally occur after longer periods of zero SMD than falls or flows. Figure 5 shows that slope failures in England correspond well with periods when both SMD is zero and daily rainfall is above the long term average. This relationship also applied to slope failures in Scotland but was not apparent for other types of failure.

Areas of high permeability superficial geology are vulnerable to landslide events following sudden intensive rainfall (Corominas 2001, cited Tofani et al. 2006)
Figure 6 compares daily rainfall with landslide events within the high and low superficial permeability classes. Records from the moderate permeability class are omitted (130 records). Landslides in the high superficial permeability class are associated with high intensity rainfall (51 records). Landslides in the low superficial permeability class are associated with low intensity rainfall (18 records). Pore water pressures

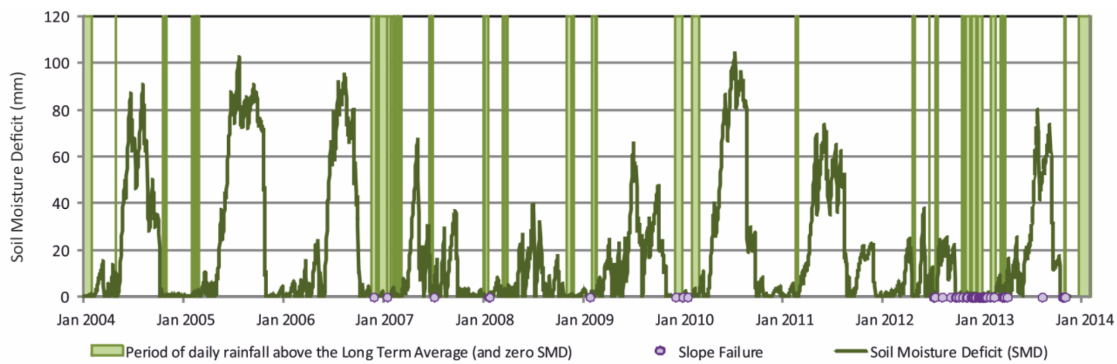

Figure 5 – Slope failures in England compared with of periods of low (< 1mm) Soil Moisture Deficit (SMD) and rainfall above the 1971-2000 long term average (LTA)

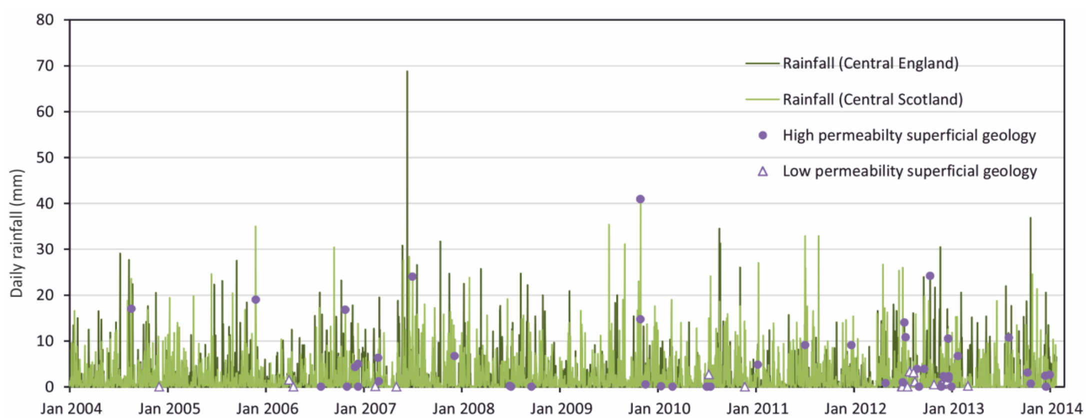

Figure 6 – A comparison of daily rainfall with landslides in areas of high and low permeability superficial geology (Table 1)

within high permeability soils are more likely to respond to intensive rainfall events and surface water infiltration than low permeability soils, where greater runoff occurs.

Preliminary results indicate that the presence of lower permeability bedrock (33 records; Table 1), does not show increased landslide occurrence during periods of zero SMD. Further differentiation of the permeability classes is required to explore the large number of landslide events in moderate permeability bedrock (257 records).

4 CONCLUSIONS

The relationship between daily rainfall, soil moisture deficit and underlying slope geology were examined using a database of 441 landslide events between 2004 and 2014.

The data shows that a combined rainfall intensity and water balance assessment can be a useful proxy for predicting slope failure type landslide occurrence when daily rainfall is above the long term average and the soil moisture deficit is close to 0 mm. However, intense rainfall (> 10 mm per day) or rapid changes in the calculated soil moisture deficit (> 25 mm per day) were not good indicators of slope failure or other landslide failure types.

Factors including the permeability of the superficial geology play a role in determining whether a slope will fail in response to an intensive rainfall event or a prolonged period of wet weather.

Further work is being undertaken to identify more localised phenomena by improving the spatial resolution of both the permeability classification and the weather data used in the SMD calculations. It is anticipated that this will benefit from continual additions to the BGS landslide database following the extremely wet winter of 2013/2014.

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REFERENCES

Birch, G. & Dewar, A., 2002. Earthwork failures in response to extreme weather. In M. Forde, ed. *Proceedings of the international conference of railway engineering*. London.

Blight, G. 2003. The vadose zone soil-water balance and transpiration rates of vegetation. *Geotechnique*, (1), pp.55–64.

Briggs, K.M., Smethurst, J. A., Powrie, W. and O'Brien, A. S., 2013. Wet winter pore pressures in railway embankments. *Proc. of the ICE - Geotechnical Engineering*, 166 (5), pp. 451-465.

Clarke, D. & Smethurst, J. A., 2010. Effects of climate change on cycles of wetting and drying in engineered clay slopes in England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 43(4), pp.473–486.

Foster, C., Pennington, C. V. L., Culshaw, M. G., & Lawrie, K. 2012. The national landslide database of Great Britain: development, evolution and applications. *Environmental Earth Sciences*, 66(3), 941-953.

Goldfingle, G., 2010. Slippery Slope. *New Civil Engineer*. Available at: http://www.nce.co.uk/ [Accessed July 3, 2014].

Guzzetti, F., Peruccacci, S., Rossi, M. & Stark, C.P. 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. *Landslides*, 5(1), pp.3–17.

Leroueil, S. 2001. Natural slopes and cuts: movement and failure mechanisms. *Geotechnique*, (3), pp. 197-243.

Lewis, M., Cheney, C. & Dochartaigh, B.O., 2006. Guide to permeability indices.

Macdonald, G.J., Vooght, a. R. & Parkin, S. 2012. The use of soil moisture deficit as a trigger mechanism for targeted monitoring of earthworks slopes. *Geological Society, London, Engineering Geology Special Publications*, 26(1), pp.141–149.

Meteorological Office 2014. UK climate and weather data. Obtained either from the Natural Environment Research Council (NERC) British Atmospheric Data Centre (BADC) or see www.metoffice.gov.uk/climate/uk

Pennington, C., Dijkstra, T., Lark, M., Dashwood, C., Harrison, A., & Freeborough, K. 2014. Antecedent Precipitation as a Potential Proxy for Landslide Incidence in South West United Kingdom. In *Landslide Science for a Safer Geoenvironment* (pp. 253-259). Springer International Publishing.

Petley, D.N., Dunning, S.A. and Rosser, N.J. 2005. The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities. *Landslide risk management*. Balkema, Amsterdam, pp. 367-374.

Ridley, A., McGinnity, B. and Vaughan, P. 2004. Role of pore water pressures in embankment stability. *Proceedings of the ICE- Geotechnical Engineering*, Vol. 157, 4, pp.193–198.

Tofani, V., Dapporto, S., Vannocci, P., & Casagli, N. 2006. Infiltration, seepage and slope instability mechanisms during the 20-21 November 2000 rainstorm in Tuscany, central Italy. *Natural Hazards and Earth System Science*, 6(6), 1025-1033.

Van Asch, Th.W.J., Buma, J. & Beek, L.P.H. Van, 1999. A view on some hydrological triggering systems in landslides. *Geomorphology*, 3, pp.25–32.

Wilson, R. C. 2003. Overture to a Landslide—A Seasonal Moisture Prerequisite. Climate Variability of the Eastern North Pacific and Western North America, 19, 149.

Winter, M.G., Macgregor, F. & Shackman, L. 2006. *Scottish Road Network Landslides Study - Appendix G*, Edinburgh.

Zhang, L. L., Zhang, J., Zhang, L. M., & Tang, W. H. (2011). Stability analysis of rainfall-induced slope failure: a review. Proc. of the ICE-Geotechnical Engineering, 164(5), 299-316.

Zotarelli, L., Dukes, M.D., Romero, C.C., Migliaccio, K.W. & Morgan K.T. 2010. Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). *Institute of Food and Agricultural Sciences. University of Florida*.