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Landslide risk - the impact on engineering underwriting and ways to manage it.

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1 Executive Summary

Introduction

Landslides are an ever-present risk in areas with ground slopes. Despite ever more sophisticated geotechnical analysis and ground monitoring techniques they still occur very regularly, causing significant damage and insured loss on construction sites, operational roads, railways pipelines and other infrastructure. Landslides occur in many different forms and may involve volumes of material from a few m^3 to more than $500,000m^3$, with the power to cause immense destruction. We hear about those events that impact populations or well-known locations, but many occur in remote areas with little publicity although they may still cause significant environmental changes to the local landscape.

They can occur because of natural processes including erosion, rainfall, glacial, seismic and volcanic activity, but can also be triggered by manmade processes including earthworks, vibrations due to construction or mining blasting, disruption of natural drainage paths or the release of water.

The impact of Climate Change on their frequency and severity is discussed in this paper.

Assessing the risk of loss due to landslide damage during the period of an insurance policy is a complex technical process that often has to be undertaken with incomplete information. The Underwriter needs to assess the likelihood of an extreme natural cause (over which there may be little control) weight this against the quality of risk management that is likely to be applied to manmade triggers. It is hoped that this paper will provide a basis for better understanding of the risks and provide some guidance on those measures that can be taken to improve the underwriting process of engineering risks that may be exposed to landslide.

Definitions

In determining how far the contents of this paper extend, it has been necessary to exclude certain topics which have either been covered in other IMIA papers or may be more properly covered in future papers. This paper therefore does not cover the following:

- Underwater landslides
- Cofferdam failures
- Tailings dams
- Consequences of landslides in terms of the form of resulting damage (although we discuss the scale of damage that results from a landslide to give an indication of how significant they can be)
- Liquefaction associated with seismic activity where a landslide is not involved
- Lava flows from volcanic eruptions (but not excluding landslides triggered by an eruption)
- Sea level rise, coastal erosion, and flooding.

2 Different forms of landslide and the most common causes

Introduction
There are many ways to describe a landslide. This section looks at some of the most important features and causes that influence the scope and scale of such an event. There are several technical terms included, which will provide the reader with a general understanding of these features and causes, aiding the understanding of the underlying loss potential and the insurance risk.

Landslide Movement
Some common terms used to describe how a landslide moves include the following:

- Falls, topples,
- Translational slides,
- Lateral spreads,
- Flows.

A classification system based on these parameters is shown in Table 1
These are illustrated in Figure 1 below.

Type of movement		Types of material		
		Bedrock	Engineering Soils	
			Predominantly Coarse	Predominantly Fine
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rock slide	Debris slide	Earth slide
	Translational			
Lateral Spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex	combination of two or more principal types of movement			

Table 1. Types of landslides. Abbreviated version of Varnes' classification of slope movements (Varnes, 1978).

Falls: Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs (fig.1D). Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

Topples: Toppling failures are distinguished by the forward rotation of a unit or units about some pivotal point, below or low in the unit, under the actions of gravity and forces exerted by adjacent units or by fluids in cracks (fig.1E).

Slides: Although many types of mass movements are included in the general term "landslide," the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides.

- Rotational slide: This is a slide in which the surface of rupture is curved concavely upward, and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (fig.1A).
- Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (fig.1B). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (fig.1C).

Flows: There are five basic categories of flows that differ from one another in fundamental ways.

- **Debris flow:** A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope (fig.1F). Debris flows include <50% fines and are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. Debris flows commonly mobilize from other types of landslides that occur on steep slopes, where these are heavily water saturated and consist of a large proportion of silt and sand-sized material. Debris-flow source areas are often associated with steep gullies, and debris-flow deposits are usually indicated by the presence of debris fans at the mouths of gullies.
  Fires (or deforestation) that denude slopes of vegetation intensify the susceptibility of slopes to debris flows.

- **Debris avalanche:** This is a variety of very rapid to extremely rapid debris flow (fig. 1G).

- **Earthflow:** Earthflows have a characteristic "hourglass" shape (fig.1H). The slope material liquefies and runs out, forming a bowl or depression at the head. The flow itself is elongated and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions. However, dry flows of granular material are also possible.

- **Mudflow:** A mudflow is an earthflow consisting of material that is wet enough to flow rapidly and contains at least 50% sand, silt, and clay-sized particles. In many newspaper reports, mudflows and debris flows are commonly referred to as "mudslides."

- **Creep:** Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep:

  - Seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature.
  - Continuous, where shear stress continuously exceeds the strength of the material.
  - Progressive, where slopes are reaching the point of failure as other types of mass movements.

  Creep is indicated by curved tree trunks lines, bent fences, or retaining walls, tilted poles or fences, and small soil ripples or ridges (fig.1I).

Lateral spreads: Lateral spreads are distinctive because they usually occur on very gentle slopes or flat terrain (fig.1J). The dominant mode of movement is lateral extension accompanied by shear or tensile fractures. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state. Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced. When coherent material, either bedrock or soil, rests on materials that liquefy, the upper units may undergo fracturing and extension and may then subside, translate, rotate, disintegrate, or liquefy and flow. Lateral spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly. Often the initial failure is a slump, but in some materials movement occurs for no apparent reason.

Combination of two or more of the above types is known as a complex landslide.

Figure 1. These schematics illustrate the major types of landslide movement that are described in the previous pages. *U.S. Geological Survey - Landslide Types and Processes – July 2004* *https://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html*

Landslide Material

A landslide can involve a range of different materials depending on the location or cause. These may include a combination or all the following:

- Rock, soil, vegetation, water.
- Hot volcanic ash, mud, and lava – (if caused by volcanic activity.)
- Snow and snowmelt – (if located in a mountainous region.)

Volcanic landslides, also called lahars, are among the most devastating type of landslides.

Landslide Causes

Landslides have three major contributory factors: geology, morphology, and human activity.

Geology refers to characteristics of the material itself. The earth or rock might be weak or fractured, or different layers may have different strengths and stiffness.
Characteristics include:

- Weak or sensitive materials
- Weathered materials
- Sheared, jointed, or fissured materials
- Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)
- Contrast in permeability and/or stiffness of materials

Morphology refers to the structure of the land. For example, slopes that lose their vegetation due to fire or drought are more vulnerable to landslides. Vegetation holds soil in place, and without the root systems of trees, bushes, and other plants, the land is more likely to slide away. A classic morphological cause of landslides is erosion or weakening of earth due to water.
Morphological causes include:

- Tectonic or volcanic uplift
- Glacial rebound
- Fluvial, wave, or glacial erosion of slope toe or lateral margins
- Subterranean erosion (solution, piping)
- Deposition loading slope or its crest
- Vegetation removal (by fire, drought)
- Thawing
- Freeze-and-thaw weathering
- Shrink-and-swell weathering

Human activity, such as agriculture and construction, can help destabilize, or weaken a slope increasing the risk of a landslide.
Activities include:

- Excavation of slope or its toe
- Loading of slope or its crest
- Drawdown of reservoirs

- Deforestation
- Irrigation
- Mining
- Artificial vibration
- Water leakage from utilities

Of the potential causes (triggers) of landslides, the three most damaging are:-

Water:
Slope saturation by water is a primary trigger (cause) of landslides. Saturation can be the result of intense rainfall, snowmelt, changes in ground-water levels, water-level changes along coastlines, earth dams, the banks of lakes, reservoirs, canals, and rivers.

Landslides and flooding are closely allied because both are related to precipitation, runoff, and/or the saturation of ground. Debris flows and mudflows often occur in small, steep stream channels and are frequently mistaken for floods; in fact, these two events often occur simultaneously in the same area.

Landslides can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back up. This may result in backwater flooding with subsequent downstream flooding if the dam fails. Solid landslide debris can “bulk” or add volume and density to otherwise normal stream flows resulting in channel blockages and diversions creating flood conditions or localized erosion. Landslides can also cause overtopping of reservoirs and/or reduced capacity of reservoirs to store water.

Seismic Activity
Many mountainous areas that are vulnerable to landslides have experienced moderate rates of earthquake occurrence in recorded times. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, allowing a rapid infiltration of water.

Volcanic Activity
Landslides due to volcanic activity are some of the most devastating. Hot lava may rapidly melt snow, producing a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, destroying anything in its path. These volcanic debris flows (also known as lahars) can cover great distances, damaging structures in flat areas surrounding the volcanoes.

3 Geotechnical investigation and monitoring and their application to project design.

Introduction

Landslides are one of the major natural threats to human lives, settlements, and infrastructure, causing enormous human suffering and property losses. The best way to limit the number of casualties and avoid destruction is effective land-use planning, based on good knowledge of the landslide susceptibility, hazards and risks within specific areas. A good understanding of the structure, dynamics, triggers, history, and possible magnitude of such high-risk landslides is an important prerequisite to be able to evaluate actual hazard and to alert people before a catastrophic event takes place. This knowledge is obtainable only through complex investigations combining several different interdisciplinary methods and techniques, long-term continuous monitoring of deformation and triggering factors and by establishing early warning systems/centres.

In the above context, monitoring and early warning provides one of the most valuable ways to reduce disasters caused by landslides and slope instabilities. Monitoring should be deployed as part of a risk management package that will typically include conventional on-site investigation, as described in later sections of this paper. It has some significant advantages, enabling “real-time” data to be collected remotely over long periods of time before, during and after any disturbance caused by the project works. The analysis of this data allows a clearer understanding of how the area in question behaves in its natural state, how the project works affect this behaviour and how the area continues to react to the changes.

This information and analysis should be used as part of the design process prior to commencement, and/or to identify the need for changes in design or construction methods during the works. Post completion, continued monitoring will allow verification that the design is performing as expected or it will indicate if any mitigation works, such as the installation of additional mechanical controls, are required to prevent future movement or collapse.

From an insurance perspective, monitoring and analysis can be used to verify the cause of a loss and provide information to influence the choice of recovery or remedial actions.

Different types of mechanical and electrical/electronic systems are used to predict failure, providing early warning.
Landslide monitoring is generally categorized into three types, including:

- Traditional monitoring techniques such as observing the changes of topography and cracks on the surface,
- Remote sensing techniques such as satellite imagery analysis, synthetic aperture radar (SAR) etc.
- In-situ ground-based observation of slope movement using various instruments such as extensometers, inclinometers, and tiltmeters.

Technological development has improved the effectiveness of monitoring and data processing with automated monitoring systems having undergone vast improvements, including to monitoring sensors, cloud services, data structure and application terminals. The development of monitoring methods, equipment, and landslide monitoring systems has gradually become the focus of research and with the advent of the Internet, many research institutions around the world have established Internet-based landslide monitoring web systems.
For an example of one such system please visit the website below.

PRIME - British Geological Survey (bgs.ac.uk)

In recent decades, sensing, computing, and communication technologies have developed rapidly. Flexible and innovative designs for monitoring and early warning systems for landslide disasters have been realized by providing accurate, low-cost, and low-power-consumption wireless equipment, and many attempts are being made to develop new applications for these technologies. With the advances in wireless networks integrated with the Internet of Things (**IoT**), data from anywhere can be accessed in real time using machine to machine communication.

However, monitoring, and early warning methods have several problems that must be overcome:

- The exact locations of unstable soil masses often cannot be defined; and hence, the locations of the monitoring sensors cannot be decided distinctly. This problem can be solved by installing many simple and low-cost sensors within a possibly unstable slope.
- What items of the slope should be monitored? The observed items should precisely represent the instability of the slopes.
- Most conventional sensors, including extensometers, require skilled engineers for their installation and operation, resulting in considerable costs and limited locations of monitoring.

Monitoring options.
There are a range of monitoring devices available, but the following are considered to be the most useful.

Rain monitoring:
A time history of rainfall intensity is widely used for warning. There are many applications providing early warning based on real-time rainfall records. The criteria of issuing warnings are defined based on the current rainfall intensity and/or the cumulative rainfall during a recent period of several hours in advance.

These early warning methods based on rainfall records are advantageous as the amount of rain can be measured easily and at a low cost. By assuming the uniform distribution of rainfall intensity, a single rain gauge can monitor the time history of rainfall in each zone for an area of several square kilometres. However, such a sparse arrangement of rain gauges cannot properly detect cloudbursts, where extremely heavy rainfalls occur in limited areas.

As the criteria for warnings are decided for every area based on local area records of past slope failure events, the monitoring of rainfall only is not enough to evaluate the risk of landslide disasters for individual slopes. In view of this, it is recommended that the behaviours of individual slopes should be monitored in combination with the area monitoring of rainfall as they complement each other.

Extensometers:
Displacement (or deformation) is one of the indicators that should be monitored for individual slopes. Extensometers are the most widely used equipment for monitoring the displacement along a slope surface.

Recently, GPS and remote sensing with radar technology have also been examined for use in monitoring the long-term displacement of wide areas of slope surfaces. However, as their typical resolutions are 5–10 mm; this level is insufficient for detecting the displacement of slopes in the very early stages. In most landslides the displacement is observed continuously for several hours or days before the catastrophic failure.

In addition to the total measured displacement, the rate of displacement is often used as an index to define the threshold of warning. The thresholds of the displacement rate are determined based on the conditions of each slope.

Inclinometer:
An inclinometer is an instrument used for measuring the angles of slope/tilt and elevation/depression of an object with respect to gravity. The resulting measurement is given as an angular measurement (degrees, minutes, seconds etc.) or as a percentage with reference to a level zero plane. Inclinometers use a small mass suspended in an elastic support structure so that when the device tilts, this mass moves and causes a change of capacitance between the mass and the support. The tilt angle is calculated from the difference in measured capacitance.

Inclinometers can be used for deep-seated installations but are not generally chosen for low-cost installation over large areas due to the expense and expertise required for installation. A cheaper alternative is the Tilt sensor (see below).

Tilt Sensors:
Tilt sensors are an economically viable solution. A simple monitoring system with Micro Electromechanical Systems (MEMS) technology can measure the tilt angles (rotation) in the unstable surface layer of slopes. This system is primarily suitable to detecting the pre-failure stages of surface failures with shallow slip surfaces using a group of simple wireless sensor units placed on the slope. The sensor units periodically measure the condition of the slope at an interval of 10 min, for example. The data is transferred to a gateway unit, which collects the data from all the sensor units, and sends them to a remote data server. Thus, the data can be browsed anywhere and anytime on the Website. The data is processed by the server and abnormal behaviour of the slope can be detected and a warning issued if it exceeds set limits.

Modern developments:
New sensor units have been developed, including surface tilt sensor and multi-segment inclinometer. They are equipped with a MEMS tilt sensor as well as a volumetric water content sensor. A temperature sensor is also included to allow temperature compensation for the tilt sensor. Each sensor unit is powered by 4AA alkaline batteries and functions well in the field for a duration of more than 1 year. By attaching an optional solar battery, these sensor units can work semi-permanently without having to worry about battery replacement.

These tilt sensors are found to be effective in monitoring very slow movements, and hence, it is possible to predict the failure time well in advance using real-time monitoring.

It has been observed that variations in tilting are not always associated with peak rainfall intensities. Continuous precipitation and water infiltration increase pore pressures and reduce the strength of the soil, so it is important to consider both long-term and short-term rainfall before developing rainfall thresholds for the region. Apart from rainfall conditions, local site conditions should also be considered when developing an effective early warning system.

Optical fibre sensors:
Optical fibre sensing technology has become a popular sensing method for “health“ monitoring of civil engineering structures, due to several key advantages. These include, high resolution, small size, light weight, real-time monitoring, remote sensing, resistance to electromagnetic interference, and ease of installation. A single sensor can be directly used as a strain gauge and encapsulated into different types of transducers for the measurement of displacement, tilt angle, strain, stress, temperature, and pressure.

The safety of a slope can be evaluated by measuring different parameters using optical fibre sensors to monitor the mechanical performance of soil nails and inclinometers as part of a real time sensing network. Both the measured strain and displacement indicate a progressive rise as the time elapses, assisting engineers to adopt quick and essential measures to deal with potential landslide risk.

A different-level early warning method based on statistical analysis can be proposed, characterized by different ranges of displacement rates.

Spaceborne, UAV and ground-based remote sensing techniques:
The current availability of advanced remote sensing technologies in the field of landslide analysis allows for rapid and easily updatable data acquisitions, improving the traditional capabilities of detection, mapping and monitoring. It can also optimize fieldwork and enable the investigation of hazardous or inaccessible areas, while guaranteeing the safety of the operators.

Among Earth Observation (EO) techniques developed in the last decades, optical Very High Resolution (VHR) and Synthetic Aperture Radar (SAR) imagery represent very effective tools for monitoring applications, since very high spatial resolution can be obtained by means of the optical systems, and by the new generations of sensors designed for interferometric applications. Although these spaceborne platforms have revisiting times of a few days they cannot match the spatial detail or time resolution achievable by ground-based equipment.

Unmanned Aerial Vehicles (UAV) Digital Photogrammetry (DP), and other ground-based devices, such as Ground-Based Interferometric SAR (GB-InSAR), Terrestrial Laser Scanning (TLS) and InfraRed Thermography (IRT), have undergone a significant increase of usage, thanks to their technological development and data quality improvement, fast measurement and processing times, portability and cost - effectiveness.

Unmanned Aerial Vehicles (UAV/Drones):
An UAV is a small, unmanned aircraft programmed for dynamic flights and is popular for large scale use in low budget mapping. The UAV is remotely operated and equipped with high resolution cameras that offers the possibility to retrieve information and slope data visually and map areas faster and more flexibility than classic aerial photos.

UAV photogrammetry has the following advantages: real-time, flexibility, high-resolution, low costs. It also allows the collection of information in dangerous environments without risk.

The recent development of new algorithms for digital photogrammetry, allows the creation of high-resolution 3D images, by using compact and consumer-grade digital cameras. In the case of landslide monitoring and characterization, acquiring aerial imagery using drones overcomes some of the limits of ground-based photogrammetric surveying, such as shadowing effects, which can drastically reduce the accuracy of the resulting digital models.

The information obtained from UAV combined with the proper software can help to analyse the slope, obtaining contours and the flow of water that occurs on the slope. This method can facilitate monitoring work and provide some analysis of the slopes while saving time and energy.

Conventional survey methods such as climbing slopes can be dangerous, so the use of UAV micro aircraft or Drones for slope monitoring work should be considered as a preferred alternative, especially for high and steep slopes. In addition, the frequency of slope monitoring should also be chosen to ensure that the slope structure condition is always safe, and people are not endangered.

4 Climate Change and the impact on severe weather, groundwater regimes and drainage

Introduction
Landslides occur when rainfall accumulation reaches a certain amount and pore water pressure in the soil/rock mass reaches a critical value causing sliding. Typically, deep-seated, slow moving landslides (e.g., earthflows, slumps) are triggered or reactivated by an accumulation of precipitation over several days or weeks. In contrast, shallow, rapid landslides (debris avalanches, debris flows) usually initiate during individual intense or large storm events.

Worldwide, rain-induced landslides (including extended and intense rainfall) are the most common type of triggering events. It is well accepted that “warming of the climate system is unequivocal” and, together with more human activity causing disturbances in more remote locations, so we must expect that the number and severity of landslides will increase.

Climate Change
The influence of climate change on slope stability and landslides is also undisputable. Nevertheless, the quantitative evaluation of the related changes in climate, on landslides remains a complex question to be solved. It has been estimated that an increase in average annual temperatures of between 2.0 and 3.5^0 C is possible over the next 80 years and is likely to be accompanied by changes in precipitation (drier summer months are expected, in the south of the UK). Rainstorm intensity is also expected to increase considerably, with the current 100-year rainfall intensity occurring on about a 10-year return period.

Figure 2. Maps show projected climate variations in (A) average annual surface temperature (°C), and (B) average annual precipitation (percentage), based on multi-model mean projections for 2081–2100, relative to 1986–2005, two different scenarios. Modified after IPCC (2014).

Note:- The impact of climate change on sea level rise leading to coastal erosion and flooding is not considered in this paper.

Impact of Rainfall
As a result of climate change, more intense rainfall and higher frequencies of extreme rainfall are likely. This will result in an increase in washout and earthflow slope failures, particularly in cuttings. The intense rainfall is associated with cyclonic storms that can occur at any time of year; however, they are particularly prevalent in the summer period. Shallow slope failures and washouts on cut slopes appear to predominate.

Changes in rainfall patterns have been influencing landslides failure events and timings over the last several years.

For example, of the 252 reportable failures in 2019/2020 by Network Rail in the UK, 190 were in cuttings and 62 in embankments (Network Rail, 2021).

In the one-year period 1/04/19 - 31/3/20, 0.24% of the rock cuttings failed, 0.27% of the soil cuttings failed and 0.06% of the embankments failed. Comparing these percentages with the average values over the 17.5-year period of 1/04/03-1/12/20, then more than three times the average number of soil cuttings failed in 2019/2020, twice as many embankments failed and about two and a half more rock cuttings failed. It is evident that in 2019/2020, shallow translational failures and washouts dominate in soil cuttings, while ravelling (and hence weathering) is the dominant factor in rock cuttings (Network Rail 2021)

The general correlation between landslides failures and rainfall has been demonstrated and is to be expected. The trend of increasing numbers of earthworks failures (Figure 3) would be consistent with changing rainfall patterns, involving longer periods of prolonged rainfall in winter. A link between earthwork failure type and rainfall pattern is apparent and it is recommended that this link be explored using recent and historical data.

Figure 3: Trend for increasing monthly earthworks failures, after NR 2021

The correlation between earthworks failures and rainfall over the 2003 - 2020 period is strong and the total number of earthworks failures per month appears to be increasing. As shown in

Figure 3 each spike in the rainfall total is accompanied by a spike in the earthwork's failures, as in January 2013, 2014, 2016 and February 2020.

Rainfall and rainfall patterns, together with surface and sub-surface drainage, influence groundwater levels and groundwater flows and so influence pore pressures at deep and shallow depths. Pore pressures are critical to stability and increases in pore pressures and reductions in suctions will reduce stability.

Two features of rainfall patterns that are relevant to identifying triggers and forms of landslides failures are:

- Antecedent or cumulative rainfall (mm/day or/week)
- Rainfall intensity (mm/minute or /hour).

Antecedent/Cumulative rainfall
Prolonged rainfall can result in the following conditions:

a) Reduced suctions and increased degrees of saturation in the weathered zone.
b) The development of perched water tables within the weathered zone.
c) A general rise in groundwater levels in the body of the cut slopes and in the embankments because of infiltration over time.

Conditions a) & b) will typically trigger Shallow failures.
Condition c) will typically trigger deep-seated landslides as these generally require rainfall of long duration. As changes in pore pressure at depth are delayed, compared with changes in pore pressure close to boundaries, deep failures are generally delayed in comparison with rainfall.

Rainfall intensity.
Rainfall intensity is a factor in determining run-off volumes, run-off rates and erosive power, in combination with the permeability and suction (degree of saturation) profiles in the surficial layer.
Figure 4 below illustrates this interaction.

- Average rainfall intensity R1 divides into run-off, R2, sub-surface flow, R3, infiltration into the body of the slope, R4 and the flow held in the unsaturated zone, R5. (Figure 4(a))
- For a given average rainfall intensity and slope angle, run-off increases as cumulative rainfall increases (Figure 4(b)).
- In winter, because of antecedent rainfall, near-surface suctions are low, degrees of saturation high and run-off rather than infiltration is encouraged, particularly on steep slopes.
  In summer, infiltration through surface cracks dominates initially until the advance of the wetting front is impeded by the low permeability of the uncracked, unsaturated soil below, following which run-off dominates.
  Hydrostatic pore pressures can develop in the newly saturated and cracked zone. Intense rainfall over a short period of time can, therefore, trigger shallow slides or slumps in summer and washouts in both summer and winter. (Figure 4(c)).
- Bombardment by intense rainfall on the surface of a saturated zone which is unprotected by adequate vegetation can initiate surface erosion (Figure 4(d)). Antecedent rainfall provides the softening blows, by leading to a minimum undrained strength, and intense rainfall provides the final knockout.

Figure 4: Impacts of cumulative rainfall and rainfall intensity, after NR 2021

Based on the above, a holistic approach to water management, (catchment to outfall, integrating all drainage systems), is needed to manage landslide stability. The size, shape, and location of all natural catchments draining towards the toe of the slope should be established, in order that the water flow rates can be determined for the required design storm return periods and allowing for climate change.

Summary

The Table 2 below summarizes the known or expected effects of climate change on landslides and reveals the complexity of the links and feedbacks between the main factors altered by climate change, and their known, expected or inferred effects on landslides.

Change in Climatic Factors	Process affected	Effects on landslide response.
Increased total precipitation.	Wetter antecedent conditions. Increased weight. Higher water table for longer periods. Increased river discharge.	Less rainfall required to attain critical water content. Reduction in soil suction and cohesion. Increased shear stress. Higher water table and reduction in shear strength. Increased bulk density. More frequent achievement of critical water content. Increased bank erosion and removal of basal slope support. Higher lake levels. Higher coastal water tables. Larger drawdown events and related drag forces.
Increased rainfall intensity.	Infiltration exceeds subsurface drainage. Increased through flow. Increased surface runoff.	Build-up of perched water tables. Reduction of effective normal stress. Reduction in shear strength. Increased seepage and drag forces. Piping. Increased surface erosion.
Increase in air temperature.	Higher evapotranspiration. More abundant vegetation. Higher hydraulic conductivity. Rapid snowmelt. Reduction in interstitial ice and permafrost.	Reduction in antecedent water conditions. More rainfall required to trigger landslides. Higher evapotranspiration. Reduced infiltration rate. Higher root cohesion. Higher infiltration. Build-up of water tables, reduction of effective normal stress. Higher runoff and infiltration. Reduction in shear strength, reduction in cohesion in jointed rock masses. Reduction in rock mass strength.
Change in wind speed and duration.	Enhanced evapotranspiration. Enhanced root levering by trees.	Reduction in soil moisture. Enhanced cracking, reduction of cohesion and soil, strength. Reduction of root cohesion. Loosening and dislodging joint blocks. Removal of slope lateral support.
Change in weather systems	Area previously unaffected/affected subject to higher/lower rainfall.	Adjustments of slopes to changed weather conditions.
Larger meteorological variability	More/Less frequent wetting and drying cycles.	Increased fissuring. Widening of joint systems. Reduction of cohesion and rock mass friction.

Table 2 Potential slope stability responses to changes in climatic factors
(Modified after Crozier, 2010).

As stated earlier, the projected increase in surface temperature is expected to result in more intense and frequent rainfall events. In particular, “extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent” (IPCC, 2014). In addition, there is a “high confidence that changes in heavy precipitation will affect landslides in some regions” (Seneviratne et al., 2012).

Where the frequency and/or the intensity of the rainstorms increase, shallow landslides, including rock falls, debris flows and debris avalanches, including ice falls and snow avalanches in high mountain areas, are also expected to increase (Stoffel et al., 2014). The February 2021 Himalayan landslide which caused extensive damage to four hydropower plants is an example of this (see Case Study section page 45).

Figure 4: Map shows general areas of expected variations in the abundance or activity of four landslide types, driven by the projected climate change. Dark colours are projections from the literature and light colours are projections from this study, after Garaino & Guzzetti, 2016

Localisation of intense rainfall events makes the prediction of precisely where they may occur almost impossible. Nevertheless, advances in monitoring technologies and surveillance techniques, in combination with historical data, can lead to identification of which geologies and geometries are especially vulnerable. In such cases a pragmatic approach would be to install instrumented barriers that will provide temporary restraint and notification of an instability event.

Successfully predicting landslide hazards in large regions greatly depends on our ability to link meteorological conditions with various types and extents of slope failures. The existence of a rainfall threshold has long been discussed. When the rainfall exceeds a threshold, the number and area of landslides may start to increase.

5 A Structured Approach to Remedial works

Introduction
The remedial measures/works are actions required to recover a site or location following a landslide or for prevention of a pending landslide. They are often reactive in nature (occurring after an event) and not part of the original project design, although they may be considered during the project design and planning stages as potential actions to be used if required (documented contingency plans will demonstrate high levels of risk management by the principal/contractor).

From an insurance perspective, understanding of the various available types of remedial methods, their suitability and complexity will help to understand the potential for site recovery and loss mitigation.

Remedial measures work by reducing the driving forces or by increasing the available resisting forces, and to be effective they must achieve one or both.

Many general reviews of landslide remediation methods have been made and the interested reader is particularly directed to Hutchinson (1977), Zaruba and Mencl (1982), Schuster (1992), Bromhead (1992) and Fell (1994).

The measures generally used for landslide remediation can be divided into four major categories as defined by the IUGS WG/L Commission on Landslide Remediation (Popescu, 2001):

- Modification of slope geometry,
- Drainage,
- Retaining structures,
- Internal slope reinforcement.

The measures chosen for any remediation will depend on several factors: the type of movement (fall, slide, flow, etc); the type of materials involved (rock, soil, debris); size and location of the failure.

Landslide Remediation
To aid the inclusion of information describing landslide remediation in the standard format Landslide Report (WP/WLI, 1990), a short checklist of possible landslide remediation measures has been prepared.

Modification of slope geometry

- Removing material from the area driving the landslide (with possible substitution by lightweight fill)
- Adding material to the area maintaining stability (counterweight berm or fill)
- Reducing general slope angle

Drainage

- Surface drains to divert water from flowing onto the slide area (collecting ditches and pipes)
- Shallow or deep trench drains filled with free draining geomaterials (coarse granular fills and
  geosynthetics)
- Buttress counterforts (a buttress built against or integral with a wall) of coarse-grained materials (hydrological effect)
- Vertical (small diameter) boreholes with pumping or self-draining
- Vertical (large diameter) wells with gravity draining

- Sub-horizontal or sub-vertical boreholes
- Drainage tunnels, galleries or adits
- Vacuum dewatering
- Drainage by siphoning
- Electro-osmotic dewatering
- Vegetation planting (hydrological effect)

Retaining structures
- Gravity retaining walls
- Crib-block walls
- Gabion walls
- Passive piles, piers, and caissons
- Cast-in situ reinforced concrete walls
- Reinforced earth retaining structures with strip/ sheet - polymer/metallic reinforcement elements
- Buttress counterforts of coarse-grained material (mechanical effect)
- Retention nets for rock slope faces
- Rockfall attenuation or stopping systems (rock-trap ditches, benches, fences, and walls)
- Protective rock/concrete blocks against erosion

Internal slope reinforcement
- Rock bolts
- Micropiles
- Soil nailing
- Anchors (prestressed or not)
- Grouting
- Stone or lime/cement columns
- Heat treatment
- Freezing
- Electroosmotic anchors
- Vegetation planting (root strength mechanical effect)

Discussion
Experience shows that while one remedial measure may be dominant, most landslide repairs involve the use of a combination of two or more techniques from the above list of the major categories. For example, while restraint may be the principal measure used to correct a particular landslide, drainage and modification of slope geometry, may also be necessary.

Hutchinson (1977) has indicated that drainage is often the principal measure used in the repair of landslides, with modification of slope geometry the second most used method. These are also generally the least costly of the four major categories.

Modification of slope geometry is a most effective method, particularly in the case of deep-seated landslides. However, the success of corrective slope regrading (fill or cut) is determined not merely by size or shape of the alteration, but also by its position on the slope and Hutchinson (1977) provides details of the “neutral line” method to assist in finding the best location to place a stabilizing fill or cut.

There are some situations where this approach is not simple to adopt. These include:-

- Long translational landslides where there is no obvious toe or crest.
- Situations where the slope geometry is determined by engineering constraints.

- Situations where the unstable area is impacted by adjacent areas so that a change in topography, which improves the stability of one area may reduce the stability of another.

Schematic view of the commonly used retaining and slope reinforcement measures along with pictures illustrating two of these measures: (a) Large Diameter Caissons (lower left) and Ground Anchors (lower right). After Popescu 2001

6 Underwriting Considerations

Underwriting information, assessment, and clauses and exclusions.

Underwriters will need to carefully evaluate any risks, whether construction projects or operational, that may have sloping characteristics, or are adjacent to any. This can range from a simple road or railway line of 10 metres to a mega hydro project built in a valley hundreds of metres high. Obvious risks that will require thorough evaluation will be those on hill or mountainsides, but can also be manmade aspects of a risk such as cuttings, embankments, etc.

Linear risks, those such as long roads, railways, pipelines, above ground hydro penstocks, transmission & distribution lines, etc., will be at greater risk due to their length exposure. But equal care needs to be given to smaller risks such as residential or municipal buildings.

The best way to assess a risk is to see it in real life, talking with those that know it well. (See Surveys in the next section).

Initial information should be a full overview of the project or operational risk from intermediaries. Such information should include:

- What is the project about, what is its purpose?
- Drawings
- Geotech report – highlighting water table, type of soils - as some will be more vulnerable to water erosion. Geotech reports should include recommended methodology.
- Full details of gradients of slopes.
- Method statements, including any risk mitigation measures such as drainage (permanent or temporary), anchoring, monitoring equipment, etc. (as per section 3).
- Full details of materials used
- Contractor experience in same or similar projects with the same geographical characteristics. From this it may be whether they are used to the same ground conditions as the new project.
- Duration, weather conditions, hydrological & metrological information/data.
- Full break up of contract value.
- Details of access roads, both permanent and temporary.
- Any blasting involved. Blasting can cause unstable ground to move and any such activities must be carefully planned, with human safety a priority.
- Details of any nearby Third-Party properties.

Location

The key driver for assessing the risk of landslide will be the location. This is where the information of topography is critical. Remembering that even a short slope can have a landslip.

- **Terrain Characteristics.**

This is particularly important when evaluating infrastructure projects.
However, the assessment should not focus only on the insured element itself. All the surrounding areas also must be assessed because in these kind of projects other preparatory and complementary works must be undertaken to enable the construction of the main infrastructure piece. For example, the construction of a road can only commence after stabilizing the slope that will be next to the road.

Topography

The Underwriter should check that slope stability studies have been reviewed and any recommendations have been or will be completed by the contractor.

- **Hydrology of the region – Flood characteristics of the geography:**

Statistical data with respect to hydrology and expected flood return period of the location should be identified and appropriate risk mitigation actions taken to minimize frequent possible flood effects.

- **Underground Water Level:**

The water retention characteristics of the soil must be assessed, and any precautions identified by drainage studies should be followed. Borehole studies carried out before the design of the project should be undertaken along the entire proposed route.

- **Stratigraphy of the zone - Soil behaviour assessed with the aid of boreholes results**

With aid the of borehole studies, the strata layers and the behaviours of each soil strata should be assessed. This is particularly important for underground projects, as for example, in a tunnel project, the behaviour of each strata segment is a critical aspect in deciding the axis of the tunnel sections.

- **Soil improvement techniques if needed (Piling, grouting etc.)**

After the determination of the stratigraphy, soil improvement techniques may be required to increase the load bearing capacity of the soil. Some examples of this may include anchorage works, jet grouting, application of geotextiles works, piling, retaining walls etc.

- **Topographic map, Slopes**

The inclination of the risk is important for deciding on the type of the construction methodology required to diminish the potential of a landslide, i.e. the designer should decide on the most appropriate method to cover the distance (i.e. with viaduct, bridges, overpass/underpass, cuts/fills and/or underground tunnel).
This is critical in terms of the financial flow of the project.

Slopes of cut and fill excavations are particularly sensitive to the influence of natural catastrophes and the following measures are necessary to prevent the collapse of slopes due to natural disasters:

- Conducting a full soil investigation prior to the construction works.
- Slope protection works must be studied in detail.
- Gradient and pitch of the slope must be correctly determined.

Nat Cat

Nat Cat exposures can increase the landslide exposures greatly. Heavy rain causes many and having the rainfall data will highlight this risk. It is then important to know what measures contractors or operators of infrastructure will take to reduce risks.
Key aspects will be:

- What time of year some critical works are carried out and also drainage measures?
- Whether temporary or permanent, will be in place.
- It is important to know what design criteria such protection Is built to (ie. One in 50 years). Method statements must include protection measures.

Endorsements for this kind of CAT exposures (not related to Earth movement) are normally required by the Underwriters to control the exposure. These include endorsements such as:

- MR 005 - Special conditions concerning the construction and/or erection time schedule,
- MR 106 - Warranty concerning sections
  or
- MR 110 - Special conditions concerning safety measures with respect to precipitation, flood, and inundation.

Where the risk is located in a high Earthquake exposure zone, frequent seismic behaviour at location may lead to severe movement of the soil. This is especially relevant for linear projects and in these cases the design criteria of the local earthquake codes must be followed, and the site should be monitored during the project period.

Contractor/Operator experience
Projects where landslides occur are often located in isolated areas, the works to build a slope, or on a slope, are complex and demand a high level of expertise and know-how from the contractors. It is critical that the contractor/operator has experience working on similar risks, and in similar topographic conditions. Given the nature of contractors working outside their home countries there have been many instances of losses from a local lack of understanding of geological conditions.

The lack of local knowledge can also show up in the wrong choice of materials where contractors simply use the same materials, they would use in their home countries. It is always good to have presence of experienced local engineers on site.

Also, with foreign contractors and multinational workforces comes the risk of different languages and difficulties in communication on site between different nationalities. Lack of communication may be found at the root of many problems in the world.

Accessibility
Accessibility, particularly for projects, is a key consideration. The topography will often provide challenges in constructing a road of suitable strength and quality to allow for the movement of materials and labour. Consider the number of trips heavy cement trucks may have to make for some projects.

Access roads, particularly temporary, usually won't have too much investment made in them as they are not intended for long term and/or frequent use. As such it may not have the level of ground investigations of the main project, and the quality may be such that it can easily erode from works traffic. The surface may simply be compacted ground that could suffer from heavy, or even average rainfall, making it impassable. The potential for aggravated claims would need to be considered where DSU or BI coverage is provided.

Another consideration for access roads is any issue with landowners. There have been many cases where landslides may have affected access roads but permission to enter landowner's property for repairs, or to allow works traffic to by-pass, has seen extremely difficult negotiations which can increase the cost of rectifying losses and extending outage periods.

Another consideration, particularly for road projects which use 'borrow pits' for materials – basically a quarry for mineral materials – these can often be taken out of hillsides which might present their own landslide exposures.

Access roads should have a reasonable sub-limit both for each and every loss and in the aggregate. Underwriters might need to determine if access roads should be included for coverage at all.

Third Party Liability

Third Party Liability (TPL) will need to be considered. Often risks that might be susceptible to landslides can be in remote locations. In such cases loss of life exposure may be low but the blockade of a road or rain infrastructure can be extremely inconvenient to business and public, creating additional costs.

Where a risk is adjacent to existing properties or infrastructure on hillsides, mountains or slopes will be a high exposure. Any landslide/landslip event could cause loss of life and/or property. Contractors will need to be extremely diligent to not cause any land movement or remove, erroneously, any existing supports.

Camps & Stores

A less considered exposure is the temporary location of camps and stores. It is usual to place these as close as possible to the project, but the safety of workers and public is paramount. As such, siting of camps must ensure safe locations away from possible landslide. Particularly where DSU is covered any loss of camps may mean the workforce has to leave site until adequate replacement facilities are provided.

Delay in Start-up/Advanced Loss of Profits

Risks that include coverage for DSU/ALoP will require special assessment. A full financial statement is required to assess whether the targets are reasonable, and how any delay might impact a project.

Given the often-remote locations underwriters must consider:

- Ability to get repair materials, labour, and equipment (CPM) to the site of any loss. It may be that a landslide has cut the project off from temporary or access roads (and also afore mentioned issues with landowners).
- The nature of landslides can be that often people and property are buried underneath. It takes time to delicately investigate and attempt to rescue.
- Government investigations – for large projects with public interest any losses will usually require lengthy investigations.

From the above it can be noted that the amount of time delay can be very high so time deductibles will need to be sufficient.

Removal of Debris

Following a landslide, the key activity will, after ensuring protection and/or rescuing of lives, be the removal of debris. Such costs can be extremely expensive following large events. Consideration of a reasonable Removal of Debris sub-limit is required, which might also be reinforced by Munich Re **Endorsement 111 – Special conditions concerning removal of debris from landslides.**

This endorsement is intended to limit expenses incurred to that of '*excavating the original material from the area* affected'. It is further reinforced by excluding '*expenses incurred for the repair of eroded slopes or other graded areas if the Insured has failed to take the measures required'*. Note that this endorsement may to be strengthened by stipulating the measures expected to be carried out by the Insured.

Operational risks
Most of the above information can apply to operational risks. Key considerations will be:

- The location, including topography.
- Knowing the design, who built it, when, and their experience in similar construction.
- Updated values
- Age of the infrastructure. This will also determine maintenance requirements and upgrades where necessary.
- What maintenance is carried out. Many think that mass concrete structures, for example, don't require much maintenance.
- Drainage in place to allow safe and adequate run-off of heavy rainfalls and snow melt.
- How the surrounding areas are monitored for avalanche/landslides, that may affect the risk.
- Nat Cat exposures. Mainly earthquake and heavy rains.
- Loss history.

Applicable Endorsements
It is recommended that the following insurance clauses should be considered in case of landslide exposed risks: **(**See also Appendix 1)

- Endorsement MR 005 - Special conditions concerning the construction and/or erection time schedule
- Endorsement MR 106 - Warranty concerning sections
- Endorsement MR 110 - Special conditions concerning safety measures with respect to precipitation, flood, and inundation
- Endorsement MR 111 - Special conditions concerning removal of debris from landslides
- Endorsement 115 - Cover for designer's risk
- Endorsement 120 - Vibration, removal or weakening of support
- Endorsement 121 - Special conditions concerning piling foundation and retaining wall works
- Subsoil and Soil Mass Clause

Some consideration might be made for aggregate limits in respect of risks that are exposed to frequent and numerous landslides.

Claims settlement issues
This paper does not go into claims settlement issues, but considerations include:

- One of the biggest current concerns in assessing a Construction Project or an Operational Risk that includes elements potentially exposed to landslides is to ensure that improvements will not be part of the claim.
- After a loss caused by a landslide, an important part of the repairment is to re-build the slide zone next to the damaged element. In most of the cases, this repairment could include changes to the design, the use of different materials or more sophisticated construction technology.
- To avoid misunderstandings that could occur during the loss adjustment, the claims expert should carefully review all the technical details to identify what is covered and what is not.
- The underwriters should always pay special attention to the policy wordings, to bring clarity to the coverage and avoid ambiguity.

Many South American markets are including a “Subsoil and Soil Mass Clause” in the Insurance Conditions. By doing this they are trying to establish a way to determine the extra expenses that post-loss re-construction of some kinds of infrastructure demand. In this way, some grey zones in the policy coverage are reduced.

7 Surveys and risk management

Introduction

Prior to any construction project, it is essential that as part of the design proposal, the scope of the works and the local conditions are fully understood. This will include the identification, assessment, and quantification of all the pre-existing and foreseeable risks likely to be encountered during the works**.**

Construction contracts typically include a surface survey to verify the site topography, access and visible features. However, for major construction or infrastructure projects a survey of the geology and sub surface conditions should also be considered as this will reveal the potential for seismic and landslide events that may not be readily apparent from a typical surface survey.

Operational risks, including CECR, can in some respects be easier to survey as the finished project is there in front of the eyes. However, critical information on installation methods (drainage, anchoring, materials, monitoring techniques, etc.) will need to be available, as well as having key technical representatives from the owner/operator for input.

As discussed earlier in this paper, landslides have many contributory causes and triggers, and these can only be positively identified and assessed by experienced engineers using a range of geotechnical survey techniques. Monitoring is one such technique that has been covered earlier. These section concentrates on the physical site survey and investigations that will usually be required as part of any proposed monitoring and analysis program.

It should also be understood that detailed site surveys as described below will usually be required as part of a post loss investigation to identify root causes and appropriate remedial actions.

Surveys and risk management

Site surveys collect information using a variety of techniques including visual inspection, sampling and installed monitoring/measurement equipment.

The most common reasons for survey demands are:

- Regular monitoring of existing slopes (property/CECR) as part of a maintenance or management program.
- Construction works (excavations, earth fill) monitoring.
- Emergency survey after near-loss situation, severe damage, and partial or complete collapse.
- Post Loss adjustment and root cause investigation.

To be most effective on-site surveys should be carried out in a planned and organised manner and this section outlines a planning structure that will ensure the best results.

A big driver of the opportunity to carry out surveys, both for construction and operational risks, will be the premium and/or Risk Engineering Fees available to pay for such activities. Some might consider that risks with a sum insured greater than USD 50m as a trigger for survey requirements. Often a Risk Engineering fee of anywhere between 1% to 5% (typically 2.5%) might be charged by the lead insurer/reinsurer, or broker, to carry out Risk Engineering. The cost of surveys might be dictated by the ease of access to site, and getting a Risk Engineer of the right expertise.

Staff selection.

- Surveys should be managed by senior geotechnical engineers or geologists with more than 10 years of design and construction experience.
- If the senior specialist cannot go to the site in person, she/he should select a geotechnical engineer or geologist with at least 5 years' experience to be the survey team leader and instruct them how to obtain the required information.
- The senior specialist should be in regular communication with the survey team to provide technical support and guidance where required.
- The senior specialist should assist the team with the review of the findings and their interpretation, ensuring that the final report presents balanced and un-biased risk assessment and technical advice.

In addition to the senior specialist, the survey team should be composed of one or more assistants, a technical representative of the slope owner/manager, and sufficient staff to perform the various planned site activities, such as transport and install equipment, perform small excavations, extract samples etc.

Surveys - Planning and Execution

Time management is an important part of the survey planning and execution because the available time on-site is frequently limited and/or initial results are required quickly. To aid this, planning and execution should be divided into the following phases to ensure efficient use of time and resources.

Phase 1 - **Initial planning and data acquisition**.

The responsible engineer must clearly understand the main purpose(s) of the survey, which may include some or all the following:

- Safety assessment, Identification of urgent retaining/protection works, damage diagnosis, defining improvements or remediation actions, long-term monitoring, post-loss assessment and others.

In preparation for the site works, it is recommended that the following planning and data acquisition is carried out. Identify the survey techniques and make available the resources required to complete the site works.
These will typically include:

- Manpower, equipment, instruments, access/permits etc.
- The survey team leader should request the owner's representative to supply details of the main design, construction, and maintenance information to increase the understanding of the asset being surveyed.
- Agree a sequence of site observations and questions to the owner. These will aid the elimination of hypotheses that do not explain the general findings and will reduce the time needed for the establishment of a clear understanding.
- Collect historical data including rain data, site history and anything else could be useful for the sound diagnosis of the slope conditions.
- If equipment such as sample extractors, excavation machinery, monitoring instruments, and scaffolding are required, then sufficient lead time should be included for the preparation to better use the on-site time.
- Photographic records should be obtained if available.

Phase 2 - **The onsite investigation**.

The second phase of the survey is the on-site investigation that should follow an agreed schedule of observations and testing. These will include some or all the following:

- Mapping and surveying the slope and surroundings,
- Making observations, measurements, and sample extracting,
- If necessary, the survey team leader should guide the installation of monitoring instruments.

The survey process should include an in-depth visual investigation looking for the following:

- Cracks, movements, slope creep,
- The presence of stabilization berms,
- The presence and condition of the existing site drainage,
- Signs of settlements, scars, superficial damage (scour),
- Water presence/surge,
- The general site surroundings (geological conditions, environment, rain, vegetation)
- Indications of any similar damages or landslides close to the site.

Photogrammetry
Topographic mapping with ground level photos, UAV (Unmanned Aerial Vehicle)/drone photos and video recordings should be obtained.

Site Monitoring

- If necessary, geotechnical monitoring instruments and benchmarks should be installed.
- Review the location and physical conditions of any existing monitoring instruments and analyse any data.
- At the end of the survey, a wrap-up meeting should take place onsite with the owner's representative to outline any urgent actions required and future observations/ monitoring to be carried out.

All field observations, test results and instrument data should be clearly and accurately documented to ensure that the findings can be thoroughly analysed and interpreted as part of the reporting process.

Phase 3 - **Review of information and report production**.
The third phase of the survey is the review of all the information collected on-site, combined with the received information from design, construction, monitoring, or maintenance. At this stage, some calculations will usually be necessary to better understand the behaviour and conditions of the slope.

The final concept and report writing must be undertaken under the supervision and collaboration of the senior specialist.
The survey report should contain the following sections:

- A certain, most probable, or estimated diagnosis should be clearly explained based upon the most up-to-date information.
- General technical advice should be stated (such as: no action, leave/abandon, maintenance intervention, remedial intervention, or strengthening/reshaping) with the advised timeliness for start and completion.
- The proposed interventions should be ranked as emergency, immediate/urgent, required, desirable and improvement.
- A recommended date should be included for the completion of works.
- The proposed interventions must be detailed with specifications and drawings.

When the report is issued the survey leader must be available to answer any questions that may arise during the interventions. She/he should visit the ongoing works to review and check progress and to provide any additional guidance as needed.

After the completion of works, the success of the intervention should be followed-up with visual inspections and may also require some instrumented monitoring.

When a survey is demanded urgently following an emergency event, intermediate reports and drafts must be shared in a timely manner with the owner to aid the fast execution of the required actions. Later, after more information has been collected, test results are available and detailed calculations have been completed, a more mature report should be issued to provide a better assessment of the problem.

Phase 4 - **Remediation and follow up**.
The fourth stage is the follow-up of the remediation works (urgent and short-term) by providing engineering clarifications and (where necessary) encouraging the owner to complete the required works in a timely manner. This may require the use of technical information as persuasion arguments.

The slope may require continuous remote monitoring and this information should be regularly reviewed by the survey team to update their reports and recommendations if necessary.

Lessons learned should be documented and shared among the technical community to improve the general knowledge and experience of managing slopes.

Risk Management.
Infrastructure assets such as the slopes being discussed in this section will require a long-term monitoring program to ensure that over time they behave as expected and any movements/variations can be detected early, allowing mitigation to prevent unexpected movement and failures.

This program will generally include:-

- A monitoring schedule including site visits and remote monitoring (where considered necessary) to regularly assess the behaviour of the assets and feed updated information to an asset management system.
- A classification system should be established in advance of all re-surveys that provides guidance detailing how to consider and weight any indications of changes, their severity and how this relates to the prioritisation of mitigation actions.
- By ranking the survey findings for each asset of a highway or railway (for example), it is possible to have a clear plan of the future maintenance actions and their potential costs. This provides the asset owner with an on-going resource allocation plan.

8 Conclusions and Recommendations

Ground Investigation
Most landslide losses, or subsidence and landslip for that matter, often have a lack of ground investigation cited as the primary lapse. Given competition nowadays for cost such activities may be susceptible to cost cutting. This is the key area where costs must be ignored and the necessary information obtained, as this will dictate how the project will be managed and built. It should go without saying that those carrying out the investigations must be of the requisite quality.

Further, economic growth and urbanization has led to more projects/risks in areas with a high exposure of landslide disasters. Therefore, the demand for mitigation measures against landslide disasters is on the rise in every country. Typical measures to prevent slope failure are retaining walls and ground anchors, however they are costly, and result in a limited number of applications. Most of the times it is not feasible, from a financial viewpoint, to reinforce all of the high-risk slopes by means of mechanical methods. In addition, mechanical methods often damage the eco-system and the landscape around the slopes. So monitoring and early warning provides one of the most valuable ways to reduce disasters caused by landslides and slope instabilities."

Drainage
Availability of adequate drainage across the site/property is also a driver of claims. Underwriters must investigate and ensure drainage in place match a minimum 1 in 100-year rain-event. Drainage also needs to be maintained. In some areas it is important that the effectiveness of drainage is regularly checked and additional drainage added if ground water is to be maintained at a safe level.

Climate Risk/ESG
Humans are entering into more and more complex and remote locations to build projects. Such locations also present climate risk issues. i.e. hydropower plants and roads are going higher in the Himalayas and global warming is causing snow melts and huge mudslides and debris flowing down as a result. Also, insurers and brokers alike must consider the Environmental Social and Governance (ESG) impact for their companies, and the need to do the right thing. Do insurers want to be associated with these?

Existing constructed slopes will have been designed with certain assumptions made about climatic conditions. If these assumptions are invalidated by a changing climate slope stability may need to be re-evaluated before it can be assumed to be adequate.

Monitoring
Ground monitoring equipment is critical to ensure safety of life and property, and good monitoring plan will help to avoid landslides, and help to ensure a project is built to the required specifications.

Risk Engineering
Another critical recommendation is to ensure that any Risk Engineers assessing such risks have the requisite expertise to understand the exposures. Risks in hilly or mountainous areas have complex issues and experienced expertise is essential. Risk Engineers should be of a Geotechnical background where possible. For insurers/brokers that don't have such disciplines internally should ensure satisfactory third-party resources are available.

Endorsements & Sub-limits
Sub-limits must always be considered and reflect the risk. For several years Underwriters agreed to any limits as a result of a soft market, but they must now attempt to cap their

losses/exposures where possible. Access Roads and Removal of Debris are key issues highlighted in the document, but there are many others to consider. Model endorsements are available but need to be understood and used where appropriate if risks are to be properly underwritten.

9 References

Section 2

- National Geographic Society – Landslide – March 2014 https://www.nationalgeographic.org/encyclopedia/landslide/
- U.S. Geological Survey - Landslide Types and Processes – July 2004 https://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html

Section 3

- Ber. Geol. B.-A., 82, ISSN 1017-8880 – Landslide Monitoring Technologies & Early Warning Systems
- Dongxin Bai, Jingtian Tang,Guangyin Lu ,Ziqiang Zhu,Taoying Liu &Ji Fang - The design and application of landslide monitoring and early warning system based on microservice architecture – May 2020
- Masiri Kaamin, Mohamad Shahir Mazuki, Aziman Madun, Nur'ain Idris, Siti Noraiza Ab Razak, Norhayati Ngadiman, and Ahmad Hakimi Mat Nor - Visual Slope Inspection using Unmanned Aerial Vehicle (UAV) - 2019
- Minu Treesa Abraham, Neelima Satyam, Biswajeet Pradhan and Abdullah M. Alamri - IoT-Based Geotechnical Monitoring of Unstable Slopes for Landslide Early Warning in the Darjeeling Himalayas - May 2020
- Nicola Casagli, William Frodella, Stefano Morelli, Veronica Tofani, Andrea Ciampalini, Emanuele Intrieri, Federico Raspini. Guglielmo Rossi. Luca Tanteri and Ping Lu - Spaceborne, UAV and ground-based remote sensing techniques for landslide mapping, monitoring and early warning – March 2017
- Taro Uchimuraa, IkuoTowhataa, Lin Wang, Shunsaku Nishie, Hiroshi Yamaguchi, Ichiro Seko, Jianping Qiao - Precaution and early warning of surface failure of slopes using tilt sensors – May 2015
- Yongqiang Hu, Chengyu Hong, Yifan Zhang and Guowei Li – A monitoring and warning system for expressway slopes using FBG sensing technology - April 2018

Section 5

- IUGS WG/L Commission on Landslide Remediation (Popescu, 2001).

Section 6

- Highland, L.M., and Bobrowsky, Peter, 2008, The landslide handbook—A guide to understanding landslides: Reston, Virginia, U.S. Geological Survey Circular 1325, 129p

10 Appendixes

Appendix 1 – Applicable Endorsements

The following insurance clauses may be considered in case of landslide exposed risks:

Endorsement MR 005 - Special conditions concerning the construction and/or erection time schedule

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon, the following shall apply to this insurance:-

- The construction and/or erection time schedule together with any other statements made in writing by the Insured for the purpose of obtaining cover under the Policy as well as technical information forwarded to the Insurers shall be deemed to be incorporated herein.
- The Insurers shall not indemnify the Insured in respect of loss or damage caused by or arising out of or aggravated by deviations from the construction and/or erection time schedule exceeding the number of weeks stated below unless the Insurers had agreed in writing to such a deviation before the loss occurred.

Deviation from time schedule: …… weeks

Endorsement MR 106 - Warranty concerning sections

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon, the Insurers shall only indemnify the Insured for loss, damage or liability directly or indirectly caused to or by embankments, cuttings and benchings, ditches, canals or road works if these embankments, cuttings and benchings, ditches, canals or road works are constructed in sections not exceeding in total the length stated below, irrespective of the state of completion of the insured works, and the indemnification for any one loss event shall be limited to the cost of repair of such sections.

Maximum length of section: ……. metres

Endorsement MR 110 - Special conditions concerning safety measures with respect to precipitation, flood, and inundation

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon, the Insurers shall only indemnify the Insured for loss, damage or liability caused directly or indirectly by precipitation, flood, or inundation if adequate safety measures have been taken in designing and executing the project involved.

For the purposes of this Endorsement adequate safety measures shall mean that, at all times throughout the policy period, allowance is made for precipitation, flood and inundation up to a return period of 20 years for the location insured on the basis of the statistics prepared by the meteorological agencies.

Loss, damage, or liability resulting from the Insured’s not immediately removing obstructions (e.g. sand, trees) from watercourses within the construction site, whether carrying water or not, in order to maintain free waterflow shall not be indemnifiable.

Endorsement MR 111 - Special conditions concerning removal of debris from landslides

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon, the Insurers shall not indemnify the Insured in respect of:

- Expenses incurred for the removal of debris from landslides in excess of the costs of excavating the original material from the area affected by such landslides,
- Expenses incurred for the repair of eroded slopes or other graded areas if the Insured has failed to take the measures required or to take them in time.

Endorsement 120 - Vibration, removal or weakening of support

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon and subject to the Insured having paid the agreed extra premium, Section 2 of this insurance shall be extended to cover liability consequent upon loss or damage caused by vibration or by the removal or weakening of support. Provided always that the Insurers indemnify the Insured in respect of liability for loss or damage to any property or land or building only if such loss or damage results in the total or partial collapse.

The Insurers indemnify the Insured in respect of liability for loss or damage to any property or land or building only if prior to the commencement of construction its condition is sound and the necessary loss prevention measures have been taken.

If required, the Insured, before commencement of construction and at his own expense, prepares a report on the condition of any endangered property or land or building.

The Insurers shall not indemnify the Insured in respect of liability for:-

- Loss or damage which is foreseeable having regard to the nature of the construction work or the manner of its execution,
- Superficial damage which neither impairs the stability of the property, land or buildings nor endangers their users,
- The costs of loss prevention

Endorsement 121 - Special conditions concerning piling foundation and retaining wall works

It is agreed and understood that otherwise subject to the terms, exclusions, provisions, and conditions contained in the Policy or endorsed thereon, the Insurers shall not indemnify the Insured in respect of expenses incurred:-

- For replacing or rectifying piles or retaining wall elements:
    a) which have become misplaced or misaligned or jammed during their construction,
    b) which are lost or abandoned or damaged during driving or extraction, or
    c) which have become obstructed by jammed or damaged piling equipment or casings,
- For rectifying disconnected or declutched sheet piles,
- For rectifying any leakage or infiltration of material of any kind,
- For filling voids or for replacing lost bentonite,
- As a result of any piles or foundation elements having failed to pass a load bearing test or otherwise not having reached their designed load bearing capacity,

- For reinstating profiles or dimensions. This endorsement shall not apply to loss or damage caused by natural hazards. The burden of proving that such loss or damage is covered shall be upon the Insured.

Subsoil and Soil Mass Clause

(Widely used in South American markets and based on a clause produced by a well known Global Insurer)

Subject to the terms , conditions, limitations, and exclusions contained under the policy or any other endorsement, the Insurer will indemnify the Assured for additional expenses due to the replacement and/or consolidation of the subsoil and/or earth masses and/or surfaces and/or cuts and/or stabilization of slopes of the project that may be necessary to incur after the occurrence of a loss covered under this policy.

Limits:

___% of the loss, subject to maximum aggregate limit of ___ for the policy period.

The unit cost of the affected section of the project will be established according to the project construction and/or total contract value declared.

11 Case Studies and claims

<u>Case Study 1 Rock Slope Failure and Remediation.</u>

Summary of Paper presented by Z Cabarekapa (2019)
Geotechnical Consulting Group LLP London UK

This case study illustrates the problems facing infrastructure construction in a seismically active area. It outlines the failure mechanisms, how these were remediated and the part that monitoring played in the claim settlement.

Overview of the left bank slope Limon dam.

Introduction
The Olmos Transfer Project located in northern Peru is one of the most important water irrigation projects for the people living in the north-western desert regions of Olmos, Peru. It is being carried out by the regional government and by the government agency that is overseeing the construction of the Limon Dam. The work has been contracted to a large international infrastructure company.

The project which has been split into several smaller schemes that will see water transferred from the reservoir behind the Limon Dam on the Huancabamba River through 20 km of tunnels taking it from the eastern side of the Andes to the western side.

Regional conditions
Peru suffers from many seismic events each year, due to its proximity to a subduction zone 160km off the Pacific coast. Mostly these are relatively shallow (50-100km) but close to the Brazilian border there have been some much deeper events ((600km). Over the last 30 years, these have produced >120 with a magnitude of M5.1 or greater, in north Peru fewer events have been recorded with a magnitude of around M1.5

Site Geology
The geology at the dam site is a complex mix of extrusive and intrusive igneous rocks that are overlain by layers of colluvium and laterite soils. Surface geological mapping of the site location has shown that the predominant rock type present is a porphyritic andesite belonging to the Oyotun formation with zones of andesite breccia and volcanic tuffs. Results of x-ray diffraction testing has shown that the predominant mineral present is silica, however kaolinite and montmorillonite clays are also present, and these can be highly unstable when mixed with water. The rock mass at many locations at the site is heavily fractured due to deformation pulses experienced and the forceful intrusions of the dykes that have a NW-SE orientation on the site coinciding with the general faulting in the area. These intrusions on site have caused localised contact metamorphism in the andesite host rock and hydrothermal alteration of the surrounding andesite.

Hydrogeology
The hydrogeological regime in place around the dam site has been determined through Lugeon tests and piezometers. Relationships have been made over the years to link Lugeon test

values to specific permeabilities, which can be used more accurately to determine the hydraulic conductivity of the rock. From these test values it can be concluded that the rock mass is a permeable medium and knowing the structural geology of the site, the water is most likely to flow through the many discontinuities present.

The effects of rainfall and the reservoir water levels are also monitored through two piezometers installed at different elevations along the slope. The data collected from these instruments have shown that in general the groundwater level follows the reservoir level, showing that the slope is in a drained state.

Slope Stability Concerns

- The first major instability event occurred in September 2006 where a large rockslide occurred during excavation and reshaping of the rock slope was taking place. Over steeping of the slope (78deg) and seismic activity were suggested as being contributing factors.
- The second instability event occurred in March 2007 when a large rockslide occurred, this time destroying 20m of the Olmos-Corral Quemado highway – one of the most important routes through the Andes. This slide which was considerably larger than the 2006 event has been described as a complex event.
- The third event was in the form of an acceleration event in late May 2008. Between late April and May of that year, extensive excavations were carried out at the toe of the colluvium slope to remove the Petro Peru oil pipeline for its relocation. The acceleration period saw displacement rates increase dramatically; but had nearly ended by June 2008 when a stability inspection was undertaken. Following this event, the slope has been slowly creeping downslope at varying rates.

A report completed in March 2015 found that the slope was showing on-going creep at rates of 1-5 $mm.yr^{-1}$ with some places along the Olmos-Corral Quemado highway experiencing rates up to 10-12 mm/yr^{-}. It was also noted that a new tension crack discovered in December 2014 showed a displacement of 45mm. This was thought to be related to the creeping of the rock mass downslope creating tensile forces at the head of the slope.

A desk study into regional instabilities occurring along the Peruvian Andes highlighted that slope instability and stabilisation is a major concern for many regions. Slope instability events are usually triggered by one or more contributing factors, with two of the most important controlling factors being slope geology and geometry. Slopes comprised of hard intact rock are inherently more stable than slopes that have experienced extensive weathering and have increased amounts of clay minerals present. If these slopes have been over-steepened; by erosion, or by man-made methods such as the cut slope at the Limon dam, the material may no longer be stable and hence sliding events will occur.

Another study into previous landslide events along the Peruvian Andes have identified the following predominant triggers to movements:

- Periods of heavy rainfall. This can be seen in this case over the previous 18 months.
- Seismic movements produced by the subduction zone located off the Pacific coast.

Failure mechanisms.

The failure mechanisms present at site are complex and have been studied and analysed closely over the previous years using Limit equilibrium and Finite element analysis. These identified that existing faults and other discontinuities were the most important controlling factors because of their frequency and persistence.

- Back analysis for the rockslide in 2006 suggested that the shallow slide (1-8 m depth) was caused by wedge failure formed by intersecting joints that dip out of the cut slope at an oblique angle to the cut face.
- The failure mechanism that drove the large rockslides of 2007 were a bi-planar dip slope failure.
  Note: Natural dip slopes are typically stable, however, the factor of safety decreases significantly if the toe of the slope is excavated.
- The acceleration period in April and May 2008 showed a large increase in both surface and deeper movements. During this time, extensive excavation was occurring at the toe of the slope. An increase in vertical and horizontal movements and an increase in tension recorded by the anchor load cells indicated a dilation occurring in the slope material as well as movement. Back analysis also indicates that during this time the factor of safety for the slope may have dropped below unity (i.e. 1.0). It is believed that the increase in tension in the installed anchors then aided in the re-stabilisation of the slope, bringing the factor of safety back above 1.0.

Remedial Program

Due to the severe displacement problems experienced by the slope, extensive reinforcements have been installed to bring the slope back under control. These include the following:

- A series of primary reinforcements in the form of concrete “slab” ribs located at the base of the berms in the slope at 20m intervals. Within these ribs are a series of pre-tensioned anchors of varying lengths.
- As the analysis of the slope has developed from 2007 to present, models of the slope have also been refined and the required anchor length has been increased.
- The reshaping and unloading of the slope above the roadway. By reshaping the slope and removing material the disturbing forces acting on the slope has decreased, contributing to an increase in the factor of safety to 1.30 for static conditions.
- Kinematic analyses determined an optimal angle to decrease the risk of rock fall from the slope to an angle of 45°.
- Several secondary remedial measures that have been installed to help improve the stability of the slope including passive rock bolts in between the concrete ribs, shotcrete facings, slope drainage and a large concrete buttress installed on the downstream side of the spillway to stabilise a talus slope.

Current Stability Issues.

- The cut slope is currently deemed to be principally stable except in a 30m wide band located slightly north of the dam spillway entrance. The concerns in this section of slope are due to an increase in malfunctioning rock anchors installed to stabilise the slope.
- By November 2018, 57 ruptured or malfunctioning anchors had been identified producing a malfunction rate of about 5%.
- By December 2018, a total of 1108 anchors have been installed at various elevations along the cut slope ranging in length from 40-70 m inclined at approximately 10-12°.
- The slope continues to creep downslope at rates of up to 10 $mm.yr^{-1}$ whilst also heaving out of the slope at displacements of 10-15 mm since 2008. This can be attributed to several factors such as the geology, structural geology of the slope and the hydrogeological regime in place.
- Slope displacement data gathered from inclinometers and surface monuments was compared with local rainfall data and reservoir water level data. A preliminary study comparing the datasets has shown that there appears to be a train of events being the likely cause for the increase in failure in the anchors.
- This train of events is thought to be triggered by infiltration of water into the slope material through the uncovered upper slope and large tension cracks that are forming at the head of the slope. This water is causing swelling of the clay rich minerals,

decreasing their shear strength, and increasing the swelling pressure in the discontinuities. This promotes both vertical and horizontal displacements within the cut slope, exacerbating the natural creep movements and causing an increase in tension upon the rock anchors.

- It is highly likely that other factors are contributing to the anchor failure, and these will be occurring alongside the influences mentioned above.
- The slope is moving is several distinct blocks at different rates and orientations.
- Due to the high frequency and persistence of the discontinuities present in the slope, the nature of the slip surface becomes highly complex, and is much harder to accurately locate. It is very highly likely that the anchors have been installed through many of these slip surfaces, causing localised increase in the tensile forces in the strands which may not register in the installed load cells.

Current location monitoring.
Due to the complex geological conditions and the obvious stability issues that the engineers are faced with on the north-south slope of the Limon Dam, a wide array of instruments have been installed to aid in monitoring the slope and the movements that are taking place. The results of this monitoring scheme are compiled annually to closely track changes in the slope behaviour and to assist in refining additional remediation that may be required.

- Approximately 150 surface monuments have been installed along the face of the slope and mainly on the concrete ribs prior to the main excavation of the colluvial slope.
- A total of 22 inclinometer casings have been installed on the north-south slope at varying elevations over 4 installation periods that range in depth from 17 m – 81 m. The latest instruments installed in 2014 have been installed up to a depth of 80m, to understand how the slope is behaving and the refinement in the location of the slip surface.
- At the dam site there are 3 accelerometer clusters installed, 1 located on each abutment and 1 near the dam crest. Within each cluster there are 3 accelerometer instruments.
- There are currently 33 load cells installed across the 1108 anchors, 7 of which are not currently operational. As with other monitoring systems the data collected from load cells can be inaccurate as they can be temperature sensitive.

Case Study 2 Landslide affecting a Hydroelectric dam project.

Introduction

The landslide occurred during the construction of a Dam and Hydroelectric Power Plant across a river, with an originally designed capacity of 450 MW.

Project description

A railway line ran along one riverbank, passing through an area which had to be excavated to allow the construction of the dam. When complete, the water in the reservoir was designed to submerge the existing railway and a separate project was scheduled to permanently re-route the railway line away from the riverbank. This work was however not going to be completed in sufficient time to avoid delaying the completion of the dam.

To overcome this problem, it was decided to construct a temporary railway diversion tunnel in the hillside behind the riverbank, which was to be used for 2 years before the railway moved to its permanently diverted route further back within the hillside.

The excavation of the slope behind the bank of the river (to allow dam construction) was undertaken using a series of ‘benches’ with slopes supported by rockbolts, mesh and shotcrete.

In the slopes further behind and above the bank of the river was an area containing fossilised landslides. Owing to the location and orientation (with an estimated 150m between the slide area and the works) it was not thought that they would interfere with the dam construction works. Although this area was subject to seismic activity it was thought that, should an earthquake cause the fossil landslide areas to move, the mass of soil would likely bypass the construction site and would end up away from the construction area.

Concurrent with the dam construction works, the second project (to re-align the railway) was also taking place in the area of the bank of the river. The new alignment passed behind the existing alignment and consisted of a series of short tunnels and open sections at a higher elevation above the water level of the new reservoir.

Landslide event

During excavations for the slopes on the bank of the river some cracks were seen. Initially, these did not cause concern, but three months later movement and cracks were also discovered in the fossil landslide area and one month later a video was posted on YouTube of a local villager climbing into large cracks that had formed in the ground.

Damage caused by the landslide, which was finally estimated to contain 30 million cubic metres of earth can be summarised as follows:

- Excavations on the left bank of the river mobilised a fossilised landslide outside the boundary of the site, causing damage to the works that had been constructed to support the left bank slope.
- Two sections of tunnel which were part of the second project to permanently re-route the railway line, collapsed.

- One section of partially completed tunnel intended to temporarily divert the railway during the dam construction works was badly damaged.
- Two steel towers for transmission lines, running from a switch yard in the area, were damaged (not part of the insured project).
- A large land area (outside the project boundary) moved a significant distance resulting in cracks in the ground and unstable subsoil conditions. This threatened an operational railway at the foot of the left bank and raised the possibility that the landslide might flow into the river temporarily blocking it.

Remedial action

A remedial works scheme to stabilise the left bank of the river and the landslide area was implemented and movement stopped. In addition, the Insured removed approx. 8 million cubic metres of the landslide earth and made changes to the design of the hydroelectric project to prevent damage from a future landslide event (perhaps caused by a future earthquake).

Work on the dam, using the modified design was eventually completed and the railway realignment project was re-routed away from dam project on a new alignment.

Cause of the event

Differing opinions as to the cause of the landslide were put forward by experts appointed by insurers and appointed by the contractor.
Issues which arose included:

- Was the landslide associated with defective design by the consultants responsible for the riverbank slope works and should their professional indemnity insurance be involved?
- Did the railway works contractor, and their insurers, have a valid liability claim against the hydroelectric dam contractor which might be covered under the hydroelectric project construction insurance?
- Did the railway works contractor, and their insurers have a valid claim against the hydroelectric dam consultant and their professional indemnity insurers?
- Should the railway works have proceeded on an alignment which passed through a fossilised landslide area.

Claims settlement

The application of several special clauses within the construction policy had to be considered including:

- MR 002 Cross Liability
- MR 101 Special Condition Concerning construction of tunnels, galleries, temporary or permanent subsurface structures of installations with a limit.
- MR 111 Special Condition concerning Removal of Debris from Landslides with a limit.
- MR 115 Cover for Designer’s Risk with a limit.
- MR 120 Vibration, removal or weakening of support with a limit.
- MR 501 Third Party Liability with a limit.
- MR 512 Professional Fees with a limit
- MR 901 Special Conditions Minimisation of Loss with a limit
- Especially drafted notes applied to the policy slip.
- The law and jurisdiction clause related to the application of local law and jurisdiction.
- Differences between the local and reinsurance wording and a “follow the fortunes” clause.

Eventually claims were settled by the construction insurers for the hydroelectric project and by the construction insurers for the railway project.

Case Study 3 Landslide affecting a Hydroelectric dam operational risk.

Introduction

As per case Study 2, the landslide occurred at a dam and hydroelectric power plant in Southeast Asia with a design capacity of approx. 70 MW.

Risk description

A hydro plant had 800mm penstocks running overland from the upstream reservoir. a headpond had been created approx. one kilometre above the powerplant. The spoil from the headpond was deposited close to the crest of a mountain.

Landslide event

There were two weeks of heavy rain. The heavy loading of the spoil triggered a mud and debris landslide that destroyed large sections of the penstock.

Aggravating factors

As with most hydro plants, access for repairs is often an issue. Access roads might be temporary and can also be at the mercy of landowners. For this event there were negotiation issues with the landowners for the existing roads. There was an impasse that meant other access roads had to be created out of a combination of new and old. Given there was Business interruption coverage then insurers must determine issues such as what is actually covered under the policy, but also how to reduce BI costs.

Lessons learned

Rock spoil from mountains has the potential to be an extremely heavy weight. Such weight should not be placed close to the top of a ridge. Add to this, large amounts of rainfall in a Nat Cat prone country (which also has earthquake exposures). It must be questioned whether a geotechnical engineer was involved with this decision.

Many underwriters and Risk Engineers often take little time to assess access roads. Such roads won’t have the quality and/or care of roads that we commute on in our towns and cities. Investment is usually low, and maintenance just as low. However, particularly where there are DSU or BI coverages in place, this can greatly increase the cost of losses. Even on flat ground, these have the potential to aggravate BI periods due to wet seasons.

For underwriters they should always consider the exposures of overground penstocks, naturally in hillsides, in Nat Cat prone locations.

We estimate this event to be in the region of USD 20m.

Case Study 4 Landslide event during motorway construction

Introduction

The project of relevance to our case study is the construction of a new motorway some 88km in length in north-western Turkey. The construction of the Project included the formation of substantial cuttings in the ground that were required to provide the desired vertical alignment for the motorway. A Landslide event occurred at during construction of a large 'cut' interchange. A General view of the Interchange during construction has been provided below.

Ground Conditions

The ground conditions in this area generally comprised the Canakkale Formation of geological rock comprising the Alcitepe Member (termed Tmal) over the Camrakdere Member (termed Tmcd).

Geological mapping from the Turkish General Directorate of Mineral Research and Exploration (MTA) for the area describes the Alcitepe Member as comprising of calcarenite, limestone and sandstone and the Camrakdere Member as comprising of sandstone, claystone [or mudstone], marl [that is. calcium carbonate rich clay or mudstone] inter alia.
Ground investigations in the area of the cutting where the Landslip occurred showed the upper layers of these members were weathered to a residual soil (sandstone reverts to gravel and sand and mudstone reverts to clay and the rock mass structure is completely lost), overlying completely weathered rock (where the rock has been converted into soil but the rock mass structure remains visible).

The natural fall in the surface of the land at the location of the Landslip was a fall of some 7°. Groundwater was generally observed to be between about 1.4m and 5m depth below ground level.

Slope design

The excavated cutting slopes where the Landslip occurred had a height of approximately 30m. The crest of the cutting slope was to be at around 126.4m Above Datum (AD), and the base of the excavation at around 96m AD. The general design of the cutting slope was for three 10m high slopes cuts at 1 in 2 (vertical to horizontal, or 26.5°) separated by broadly horizontal benches some 5m wide cut into the mid-slope.

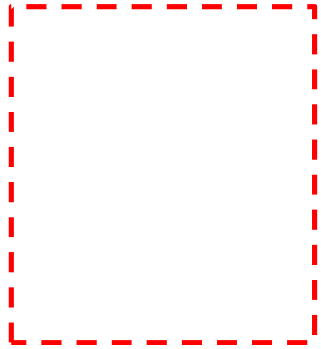
Permanent drainage channels were formed on these benches to intercept and drain away surface water and additional crest drain was positioned beyond the slope.

An underpass was to be formed below the motorway at the location of Landslip, with associated access ramps cut down into the ground. As a result, the lowest bench in this location was to initially be constructed at an angle of 1 in 1 (45°) with a wider temporary bench above, before being steepened as required for the ramp to form the permanent slope after the adjacent Underpass had been constructed and backfilled.

An Aerial overview of the interchange construction and underpass has been provided below. The section of slope that is the subject of this case study has been highlighted.

Event Details
During the construction of the highway the base of the cutting had been deepened by around 7.5m to form the excavation to construct the Underpass, generally with sides slopes of 1 in 1. Shortly thereafter, a substantial landslip occurred, with around 80m of the slope sliding into the cutting leaving a wide backscar. The length of the slipped material was some 120m.

The near vertical backscar exposed at the side of this landslip showed the interbedded layers of the Alcitepe member. A relatively smooth planar failure surface was also visible in a clay layer, on a bedding plane in the residual soil of the Camrakdere Member (Tmcd W6).
Aerial and site photos of the landslide area a have been shown below.



CAUSE

The landslip comprised a translational sliding failure of the cutting slope, sliding on a relatively weak layer with the failure plane being located in the residual clay soil of the Camrakdere Member (Tmcd W6). The bedding planes of the layers and interfaces between the Alcitepe and Camrakdere Members were found in the cutting at this location.

The sliding failure that occurred was perpendicular to the local cut slope for the Ramp adjacent to the Underpass, with around 80m of this cutting slope sliding approximately 7m towards the

cutting and affecting a length of around 120m along this slope. Based on the available survey data, the gradient of the apparent failure plane was approximately 10°.
In a technical sense, the landslip occurred because the available resistance to sliding failure in the residual clay layer of the Camrakdere member, where the failure plane occurred, was not capable of resisting the weight of the slope above.

It is therefore necessary to understand the available strength of this soil layer to resist such a failure and the stresses in the ground acting on this potential plane, which are affected by the weight of the ground above and groundwater pressures acting along this plane.

In some layers of the completely weathered claystone of the Camrakdere member there were extremely closely spaced fissures, and this soil was described as crumbly. The further weathering of this material formed a residual clay soil, which was described as moist or damp indicating free water on the surface. During the site investigation of the stiff clay layer, extremely closely spaced fissures (both sub-horizontally and sub-vertically) were observed. These acted as planes of weakness and were wet (that is, had 'free' water on their surface).
On such fissures there would be little or no apparent cohesion and the angle of shearing resistance would be expected to be at or close to 'fully softened' or fissured strength.

The cause of the landslip was shortcomings in the design of the cutting slopes relating to a lack of consideration of the potential for sliding failures on the layers of residual soil and completely weathered rock that is located at the cutting in this location. Over-optimistic strength parameters on these layers and the groundwater levels adopted in the design were too low.

A cross sectional overview showing the topography of the constructed slope, highlighting the area failure is shown below.

Remedial Program
<u>Loss Prevention</u> – Excavation and removal of soil mass, to prevent further sliding events and damage to the asset all unnecessary loads were removed.

<u>Redesign</u> – Redesign of the slope profile, from a H:V=2:1 gradient (26.6°) to a flatter H:V=3:1 (18.4°) slope. The new slope design was to reinstate the drainage channels, but also included additional features, such as a lateral drainage system and 290 metres of corrugated pipes to address adverse ground conditions (i.e. decreased slope stability) and stone pitching to add further stability at the base of the new slope. Notably, to achieve the lower slope gradient the new slope is cut further back into the hillside, and thereby extends beyond the original 'site boundary'.

Monitoring program

A groundwater monitoring programme was implemented using existing standpipe piezometers, supplemented by further piezometers such as vibrating wire piezometers that can electronically monitor the groundwater pressures at a specific level and record this at regular intervals over time, to give a clear picture of changes in water pressure over time.

The cross-sectional overview of the redesigned slope has been provided below.

Various Case Studies

There are many examples of landslides events that can be found on line. The amount that can be found also illustrates how common they are. Some of the more interesting ones are;

The Himalayan landslide of 4th Feb 2021.
This landslide has increased the focus on climate change and the entering into more remote regions in a desperate search for energy.

Himalayan dam collapse should be a wake up call for everyone over climate change risks | New Civil Engineer

Just two years previously this article highlighted the issue of retreating ice caps and the possible consequences.

Himalayan hydro developers wilfully ignore climate risks | PreventionWeb.net
Himalayan nations can no longer ignore an environmental time bomb - SWI swissinfo.ch
Hydropower projects are wreaking havoc in the Himalayas | Environment | Al Jazeera

The Atami mudslide of 1st July 2021
This event, 100km west of Tokyo, Japan left 19 dead and 9 still missing to date. It occurred after two days of heavy rainfall. Some feel that an accumulation of imported soil into the town might be a cause. It highlights the fact that landslides aren't just confined to remote mountain or hillside areas.

https://www.smh.com.au/world/asia/mudslide-west-of-tokyo-hits-houses-several-people-missing-20210703-p586ka.html

The Xizhi/Formosa Freeway landslide of 25th April 2010
This loss in Taiwan buried 4 cars and killed 4 people. The cause has been blamed on poor hillside anchoring. At the time of the event there had been little rain and no earthquake. It took nearly 2 months to get traffic flowing again.

Huge hillside collapses, covers Formosa Freeway - Taipei Times
Taiwan passes land use law after deadly landslides - BBC News

Landslide Blog
This website from a UK landslide 'enthusiast' provides regular commentary on landslide that occur. The regularity of such landslides highlights how common an event they can be.

The Landslide Blog - AGU Blogosphere