Chapter Eight:
Landslide

Site adjacent to a fatal limestone sea-cliff collapse at Cowaramup Bay, near Gracetown, southwest Western Australia, September 1996
Photo courtesy: Geoscience Australia/Brian Gaull.

Landslide

Landslides regularly occur in localised areas across Australia, and pose a serious threat to people and property. They occur over a wide range of velocities and are often at their most damaging when they happen suddenly and without warning.

The economic cost of individual landslide events is typically much lower than the cost of flood or earthquake events. Since 1842 there have been approximately 84 known landslide events, collectively responsible for the deaths of at least 107 people and injury to at least 141 people, as recorded in the Australian Landslide Database (GA 2007). Although many landslides have natural causes, well over half of the landslides that have caused death and injury can be attributed either directly or indirectly to human activity.




Cracks in the retaining wall and road from landslide activity near the head of the Lawrence Vale landslides in Launceston, Tasmania
Photo courtesy: Geoscience Australia/captured in 1996.

Vehicles caught in the run-out of a debris flow on the Bulli Pass near Wollongong, New South Wales, August 1998
Photo courtesy: NSW SES.

State Emergency Service volunteers involved in rescue efforts at a fatal landslide at Thredbo, New South Wales, July 1997
Photo courtesy: NSW SES.

Damage to a road caused by a landslide at Macquarie Pass south of Wollongong, New South Wales, February 1997
Photo courtesy: Geoscience Australia/Marion Leiba.

This chapter highlights the types of landslides which occur in Australia, and the factors which cause them. Information is provided on the risk analysis process and the data required for modelling. The basic theory of landslide processes is well understood. However, landslide risk assessments are complex and there are significant information gaps in undertaking landslide risk analyses which are outlined. The potential influences of climate change and the impact of climatic cycles on landslide processes remains a significant gap in information. The majority of landslide practitioners in Australia are in the private sector, and local governments have principal responsibility for managing landslide risk.

Hazard Identification

Landslides are a form of erosion known as 'mass wasting', which is an important natural phenomenon in the formation of slopes and in the evolution of landscapes. The term 'landslide', which encompasses a range of processes, is the term favoured by geotechnical professionals. Other terms such as 'landslip' are entrenched in legal terminology, and the general public and media may use terms such as 'slumps' or 'mudslides'.

In simple terms, landslides occur when the downward force of gravity acting on slope materials exceeds the cohesive force that holds the soil particles together, or the frictional force which holds the material to the slope (i.e. 'shear strength'). The failure of slope materials can be related to a number of contributing factors and trigger factors.

The contributing or 'site setting' factors which influence whether a landslide will occur include: steepness of the slope; shape of the hillside; engineering properties of different materials in the subsurface profile; depth to the water table (or the pore water pressures on the landslide failure surface); the potential for subsurface water concentration; and vegetation cover.

Often a number of factors will contribute to a landslide occurring. However, frequently the dominant factor which triggers the movement of slope material will be an increase in pore water pressure from rainfall or leaking infrastructure. Other triggers include earthquakes, vibrations caused by human activities, and undercutting of slopes by fluvial erosion or artificial excavation. Additional information is available in a range of texts, including Turner and Schuster (1996) and Fell (1992). The relationships between these factors are important in understanding the causes of landslides.

All factors can be influenced either positively or negatively by human activity. Although in some areas landslides may be limited to failures in uncontrolled and unretained fill or road cuttings and excavations, they still pose a risk to people and property. Consequently, it is unusual to find a populated area in Australia that is not susceptible to some form of landslide process. It is believed that all local government areas have land stability challenges of one form or another (Leventhal and Kotze in press).

Fell (1992) provides a regional overview of land instability in Australia, which describes the location and extent of landslides and the conditions and mechanisms which are conducive to slope failure. Most landslides in Australia occur in Tertiary basalt, Tertiary and Cretaceous sediments and older inter-bedded sedimentary and coal measure formations (Fell 1992). Maps which show the distribution of such materials for New South Wales, Victoria, southern Queensland and Tasmania, along with a comprehensive bibliography, are also provided in Fell (1992). Further information is provided by Johnson and others (1995), Michael-Leiba (1999), Michael-Leiba and others (1997), Blong and Coates (1987) and AGS (2007).

The distribution of reported landslide events in the Australian landscape is shown in Figure 8.1, which reflects the results of specific landslide mapping programmes based in Tasmania, southwest Victoria, Wollongong and Newcastle–Lake Macquarie in New South Wales, and Brisbane and Cairns in Queensland. The remainder of the landslides depicted were reported by the media or by 'landslide spotters'.

The types of landslides that occur in various geomorphic settings in Australia are explained below.

Rockfall

Typical settings where rockfalls may occur include cliffs in coastal zones, mountain sides, gorges, road cuttings or quarry faces. The coastal cliff lines of New South Wales (Kotze 2007) and the dolerite mountains of Tasmania are prominent examples. Rockfalls are characterised by an extremely rapid rate of movement and have been responsible for many of the landslide-related deaths in Australia. Depending on local conditions, the run-out distances of rockfalls can be considerable. Although the source areas of these features are generally too steep to build upon, popular beaches and structures such as walking tracks, roads and houses may be located in the run-out area.

The largest rockfall in Australian history is believed to be a 30 million tonne rockfall which collapsed above the shoreline of the Lake Burragorang Reservoir (Warragamba Dam) in New South Wales in 1965; the rockfall was

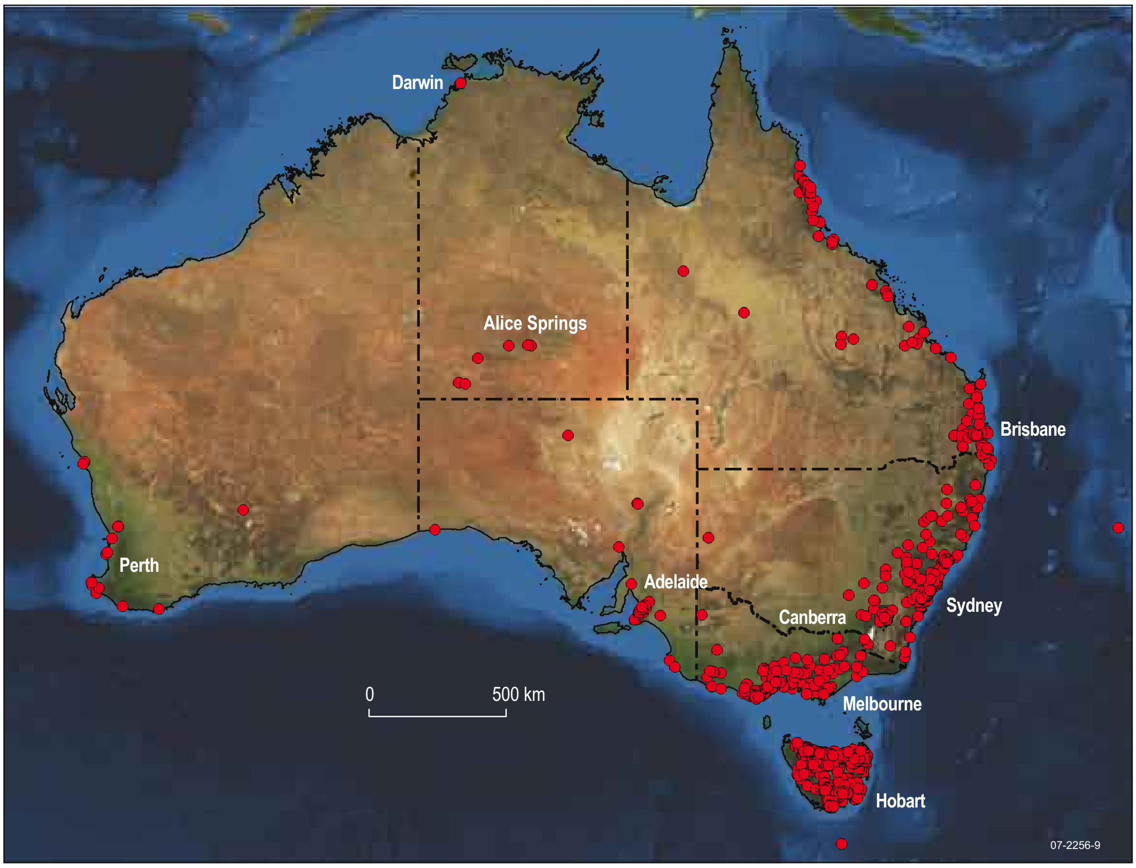

Figure 8.1: Recorded landslide events in Australia
Source: This map was compiled by Geoscience Australia in August 2007 from data available in the Australian Landslide Database (incorporating records from Geoscience Australia, Mineral Resources Tasmania and the University of Wollongong). Data for southwest Victoria were supplied by Corangamite Catchment Management Authority in association with the University of Ballarat and A.S. Miner Geotechnical.

attributed to underground coal mining (Pells and others 1987). Other examples include the rockfall at Gracetown, Western Australia, in 1996, where 30 tonnes of rock and sand fell from a limestone sea cliff onto people sheltering under an overhang, injuring three and killing nine; a 100 metre rockslide at Mulligans Bluff on the Gwydir Highway, New South Wales, in 2002; and regular rockfalls along Lawrence Hargrave Drive in Wollongong, New South Wales, including notable falls in 1988 and 2003.

Deep-seated Landslide

Deep-seated landslides typically occur in steep terrain. However, they can be observed on slopes with angles as low as a few degrees, because the geological materials involved typically have low shear strength or are subject to high pore pressure. Areas include the Tertiary basalt soils and the Tertiary sediments of eastern Australia (Fell 1992; McGregor and others 2007).

Across Australia, there are many examples of houses and subdivisions built on existing landslide sites or on slopes that are susceptible to failure. While most of these landslide sites may be dormant, some can be reactivated with changes in pore water pressures and/or disturbance through human activities such as property development.

An example of a deep-seated landslide in Tasmania is the Taroona Landslide in Hobart, a very to extremely slow-moving landslide on which two schools and nearly one hundred houses are located (Moon and McDowell 2002; Latinovic and others 2001). Monitoring over a seven-year period indicated that movement occurred at the site every year, although only a few structures were affected by the movement.

Debris Flow

Debris flows can originate on slopes in the range of approximately 16 to 40 degrees, where loose rock and soil materials are subjected to high-intensity rainfalls. Where water content is high, debris flows can travel at rapid velocities with considerable destructive potential. Houses and other structures may be situated on or near the source area or run-out path of such features.

The landslide at Thredbo, New South Wales, in 1997 became a debris flow which destroyed two buildings and claimed 18 lives. It was the worst landslide disaster in Australian history, and the ground failure was attributed to a leaking water main.

Debris flows triggered by intense rainfall include: the debris flow at Humphrey Rivulet, Tasmania, in 1972 (Mazengarb and others 2007); the slides which blocked the Captain Cook Highway behind Ellis Beach, north of Cairns, Queensland, in 1951 (Michael-Leiba and others 1999); and the 60,000 tonne debris flow at Montrose in the Dandenong Ranges of Victoria in 1891 (Moon and others 1992).

Shallow Landslide

Shallow landslides occur in areas with a shallow layer of weak material and are often triggered by brief episodes of intense rainfall. They tend to occur on the edge of embankments and on steep natural slopes of 30 degrees or more. The infrastructure most commonly affected is roads and railway lines, although shallow landslides occasionally damage houses and other private property.

Numerous shallow landslides occur during the wet season. For example, they are often associated with tropical cyclones in the Cairns region and along the Cairns–Kuranda railway (Michael-Leiba and others 1999).

Cost of Landslides

The financial and social consequences posed by landslides are extremely underestimated in Australia. Landslides regularly damage buildings, roads, railways, vehicles, pipelines and communication lines, and have adverse social effects that include death, injury, stress

Damage to a road caused by a slow moving landslide at Pleasant Hills, northwest of Launceston, Tasmania
Photo courtesy: Geoscience Australia/Marion Leiba/captured in 1996.

and displacement. Not only is stress detrimental from the psychological and social point of view, it also can have detrimental physical effects that may even lead to fatalities.

The total direct cost of landslides in Australia for the period from 1967 to 1999 is estimated at $40 million. This can be solely attributed to the 1997 Thredbo landslide as only landslides costing $10 million or over were included in the BTE (2001) estimate. However, for the period from 1900 to 1999 the total socioeconomic cost of landslides was estimated at $500 million in 1998 dollars (EMA 1999).

Most damage is the result of many small landslide events, and it is believed they have a significant cumulative cost. Few insurance policies in Australia cover landslides, and it is understood that the majority of landslide costs are absorbed directly by individual property owners as well as by infrastructure authorities.

Costs associated with disaster assistance and road maintenance, relocation and repair are among the greatest public costs resulting from landslides. For example, the Australian Landslide Database indicates that the construction cost of diverting the Lawrence Hargrave Drive coastal route around a cliff face subject to rockfalls was $49 million in 2006 dollars, and it is estimated that from 1989 to 1996 the cost of repairs to railway infrastructure in Wollongong amounted to $175 million. Reconstruction of the Alpine Way after the Thredbo landslide cost $24 million (BTE 2001).

Adding to the complexities of estimating landslide costs are the different types of landslide processes. The costs of extremely slow-moving landslides which cause cracks or irregularities in the fabric of buildings and in the surface of roads, footpaths or pipelines are typically absorbed into general maintenance and repair costs. Other hazards, such as tropical cyclone or flood, may trigger landslides, presenting a challenge in isolating and determining the damage that is a specific consequence of the landslide.

Environmental cost is difficult to quantify in financial terms. Landslide-derived sediment may cause prolonged turbidity in stream channels that, in turn, may adversely impact on water reservoirs or fish habitats. A significant increase in the incidence of landslides on Macquarie Island, Tasmania, is believed to be the consequence of the removal of vegetation by a rapidly expanding population of rabbits. Costs of controlling the rabbit numbers and preventing further landslides are estimated to be $24.6 million (ABC 2007; Parks and Wildlife Service 2007).

Further information on the economic and social impact of landslides in Australia is provided by Blong and Eyles (1989), Schuster (1996), and Michael-Leiba (1999).

Potential Influence of Climate Change

In geological time, climate change has been extensive and has had a profound influence on sea level, rainfall patterns, and temperature-related hillside processes such as chemical and mechanical weathering. Climatic phenomena, such as the complex interactions of the Interdecadal Pacific Oscillation Index, the El Niño–Southern Oscillation (ENSO) and the deep-ocean conveyor cycle, have impacted on the short-term and long-term rates of mass wasting in Australia, which span from decades to thousands of years and longer. Further information on these interactions is available in Kiem and others (2006).

Rainfall patterns are significant to landslide occurrence. Conceptually, it is almost a certainty that predicted climate change will impact on the rate and severity of landslide hazard to some degree. More frequent high-intensity rain in some areas could be expected to increase the likelihood of landslides and erosion, particularly in the urbanised catchments on Australia's east coast (CSIRO 2002).

Potential impacts of climate change include increases in sea level and temperature and a drier climate.

A rise in global sea level in the order of 0.09–0.88 metres by 2100 (Solomon and others 2007) will have an influence on Australia's coastal environments, accelerating the erosion of sandy dunes along soft coasts and cliffs along hard coasts.

A drier climate will lead to a drawdown of the water table, and may reduce the likelihood of deep-seated landslides, debris flows and intermittent slip-stick movement. For instance, a marked drop in annual rainfall from 1975 to 1976 was reflected in a drop in landslide activity in Tasmania (Ezzy and Mazengarb 2007). However, in areas with shallow slopes of reactive clay soils, a lowering of the water table may cause 'fissuring' (i.e. cracking) on slopes. This may increase the susceptibility of the slopes to water infiltration during rainfall, which can lead to slope failure.

An increase in temperature is likely to bring more frequent and intense storms. Storms accompanied by heavy rainfall may trigger landslides and short-duration erosion. Stream flow from increased run-off may also accelerate erosion rates and undercut slopes. An example of the relationships between intense storms and increased stream flow and shallow slides and debris flows is provided by Reinfields and Nanson (2001).

Guidelines for responding to the effects of climate change in coastal and ocean engineering are outlined in Engineers Australia (2004).

Risk Analysis

Landslide risk analysis involves determining the likelihood of a particular landslide event and understanding the possible consequences of that event. The data required to model or map actual and potential landslides vary with the scale and purpose of the assessment. Modelling of landslide susceptibility, hazard and risk requires the existence of a landslide inventory, which is the fundamental source of historic information on landslide occurrence and is used to validate or 'ground truth' any models which are built.

A variety of skills are required to perform a landslide risk analysis, and the number of personnel involved might range from a single individual for a house site analysis to a team for a regional analysis.

The practice of landslide risk analysis is a requirement for a range of activities, including infrastructure development, mining, monitoring and maintenance (e.g. for hydroelectric dams and roads), and as a condition for development approval imposed by local government. It is important to note that the mining sector is an area where an advanced understanding of soil and rock behaviour is critical to ensuring safe working conditions. This specialised area is outside the scope of this chapter, though is an area where the principles of risk management are routinely applied.

Prior to the 1997 Thredbo disaster, the general public regarded the issue of landslide risk to be primarily related to loss of property (Leventhal and Kotze in press). The Thredbo landslide changed public and political perception of the hazard, and led to the formulation of guidelines for practitioners by the Australian Geomechanics Society (AGS). The suite of guidelines outlines good practice in landslide susceptibility, hazard and risk zoning for land use planning (AGS 2007a; AGS 2007b), landslide risk management (AGS 2007c; AGS 2007d) and slope management and maintenance (AGS 2007e).

Despite the guidance offered by the AGS, there remain variations in the approach to landslide risk analysis within Australia. Some practitioners find it difficult to achieve the desired standard, for reasons such as complexity and cost. A landslide risk assessment is a complex and difficult process (van Westen and others 2005) and methods are still evolving. Assessments are increasingly becoming multidisciplinary and technology driven.

Further information on risk analysis and assessment is provided by Cruden and Fell (1997), Hungr and others (2005), Miner and Dalhaus (2006), Flentje and others (2005), Flentje and others (2007), and Lee and Jones (2004); and in the reference lists of the AGS guidelines and van Westen and others (2005). Further information on the role of the AGS guidelines is provided in Leventhal and Kotze (in press), Leventhal (2007) and Leventhal and others (2007).

Likelihood Analysis

Since the adoption of a risk-based approach to landslide assessment in recent years, the estimation of landslide likelihood has proven to be particularly challenging. Estimations of likelihood are evolving from the use of relative terms such as 'possible' and 'unlikely' to semi-quantitative and quantitative approaches (e.g. Moon and Wilson 2004, and Moon and others 2005). Estimating potential movement of an existing landslide is difficult, but predicting a first-time slide is even harder. This is partly because records of past events are invariably incomplete and provide little guidance on infrequent events (Moon and others 2005).

There are at least three distinctly different landslide processes that need to be considered (i.e. rockfall, debris flow and deep-seated landslides), as well as the range of triggering and contributing factors, which may be poorly understood regionally and/or locally. Each type of landslide varies in frequency, speed and style of movement, duration and run-out distance, and has unique properties and characteristics for risk analysis and management. Additionally, for each different type of landslide process the risk analysis needs to take into consideration potential effects up-slope, down-slope, laterally and in the run-out zone.

The estimation of likelihood is a two-stage procedure for each landslide type. The first stage generates a landslide susceptibility map, and incorporation of the second stage generates a landslide hazard map. Each type of landslide needs to be analysed separately in these stages, as each is governed by a different physical process.

The first stage of analysing likelihood is to determine the susceptibility of landslides, which is a measure of the 'spatial probability' of failure. This stage considers any historic landslide occurrence and analyses the underlying site setting factors which contribute to landslides. For all three landslide processes, susceptibility analysis involves the identification of potential source areas, as well as the separate prediction of potential landslide run-out areas. Both procedures can be done in several ways using various modelling and mapping techniques. These are outlined in AGS (2007a; 2007b) and Flentje and others (2007).

The second stage is to determine 'temporal probability'. There are several approaches, as outlined in van Westen and others (2005). The temporal probability can be obtained by correlating the data on landslide occurrence with data on the triggering factors, provided data records are sufficient, or through dynamic (i.e. time dependant) modelling (van Westen and others 2005).

For example, long-term record keeping of landslide events can allow the relationship of landslide occurrence to triggering events such as rainfall to be determined (Michael-Leiba and others 2002; Walker 2007), although this relationship may not always be clear (MacGregor and others 2007). Rainfall analysis may require consideration of duration (e.g. antecedent values over weeks and months) and intensity (e.g. over a 24-hour period or shorter event), depending upon the style of landslide. The likelihood of failure can then be derived for any point on the ground by analysing the number of landslides per year, and their susceptibility, combined with the predicted recurrence interval of the rainfall conditions which trigger the landslides.

Additionally, based on observed relationships in nature whereby smaller events tend to occur more often than larger events, the analysis of magnitude–frequency relationships may further refine the likelihood modelling of event size.

Data requirements

The information required will vary depending on the type, scale and purpose of investigation. Likelihood analysis requires data to estimate the spatial and temporal probability of landslides (i.e. the landslide hazard map).

The historic information on landslide events is fundamental, as it provides an insight into the frequency of the phenomena, the types of landslides involved, the volumes of materials involved, and the damage caused (van Westen and others 2005). The data should span as lengthy a time as possible and include landslide

View from the headscarp of a fatal landslide at Thredbo, New South Wales, July 1997
Photo courtesy: Geoscience Australia.

Homes perched precariously after a major landslide on Currumbin Hill, southeast Queensland, July 2005
Photo courtesy: Emergency Management Queensland.

inventories, aerial photographs, remote-sensing data and terrestrial photography.

Historic data on landslide occurrence, in addition to the site setting factors, are important in determining landslide susceptibility. This generally requires data on topography, geology, geomorphology, soil type, soil depth, geotechnical characterisation of slope materials, vegetation, hydrology and hydrogeology. Such data, where available, are typically represented spatially as data 'layers' and analysed in a geographic information system (GIS). For example, a digital elevation model is important for modelling the run-out distance for landslides of a given type and volume.

Incorporation of data on trigger factors is required to develop a landslide hazard map. This includes the data required to determine landslide susceptibility; rainfall data sets (both raw and derivative interpretations); data on seismic hazard; and other trigger information, which may include the location and type of underground pipes.

High-resolution data are essential for undertaking likelihood analyses in localised regions. In some cases, the absence of spatial information may be replaced with the requirement for the practitioner to have sufficient understanding of the slope-forming processes operating in a particular area and the effects that individual components contribute to slope instability. Competent and skilled practitioners must be involved in the interpretation.

Consequence Analysis

The consequence of a landslide changes with temporal and thematic variations in vulnerability. For example, thematic variations include the material type of a building or the age distribution of a population. The estimation of the degree of damage should be based on vulnerability/fragility curves derived from historical damage inventories, where records are sufficient. Curves can also be derived from structural modelling or though empirical relations (van Westen and others 2005).

The exposure of mobile elements such as people and vehicles will vary considerably between day and night, and seasonally, depending on where people work and reside. The vulnerability of elements which are at risk may also vary considerably depending on the type of landslide and its rate of movement (Cruden and Varnes 1996). Typically, the faster a landslide moves, the greater the amount of damage to people and property, because speed reduces the opportunity for remedial action or escape. However, even buildings situated on extremely slow landslides may be completely destroyed over a number of years.

For landslides with potentially long run-out lengths, the destructive potential will be strongly influenced by topography, slope angle and obstacles such as forests, as well as the shape, dimensions and mass of the boulders.

Data requirements

Data on historic damages for different landslide types and volumes and information on the vulnerability of the elements at risk are required. Generic exposure databases may be utilised, although these are better suited to hazards which impact regionally per event (e.g. flood or earthquake) rather than for landslides which generally impact isolated elements (van Westen and others 2005).

Information Gaps

Worldwide, much is known about landslide processes and the potential consequences of the range of landslide phenomena. However, for most of Australia there is no ready source of landslide information relating to the local setting and Australia does not have a good understanding of how its population centres relate to landslide risk.

There is no coordinated means of data collection in Australia. Where such information exists, landslide mapping and geotechnical reporting is highly variable in standard and quality, and there is generally apprehension about sharing any information which may relate to potential issues of legal liability. There is also space to better consolidate and integrate geotechnical engineering expertise with research from domains of geology, geomorphology, hydrology, meteorology, GIS, and computation.

The primary constraints to addressing landslide research gaps are skill shortages and resource limitations. There are currently no universities within Australia that teach the holistic range of skills required to undertake landslide risk analyses. Very few engineering departments teach or research engineering geology or geology for engineers. Furthermore, it is estimated that 30,000 engineers will retire by the end of the next decade (Engineers Australia 2005). Skill shortages are particularly apparent in the civil sector, partly because of competition for skills from the lucrative mining sector.

Further information on gaps in landslide knowledge and processes is provided in van Westen and others (2005) and Leventhal and Kotze (in press).

Landslide Inventories

The AGS (2007a; 2007b) considers that landslide information should be entered into inventories to underpin all successive risk analyses, research and land use decisions. The ongoing collection and analysis of landslide data and related data is a vital exercise, although the provision of funding for ongoing maintenance of these databases presents a challenge.

A landslide inventory represents a fundamental base of knowledge for land use planning that strongly helps local authorities in their decision making. With few exceptions throughout Australia, the activity of recording landslides is currently undertaken in a haphazard way, and records are not detailed enough to be used confidently in probability assessments. Data are collected and recorded in different formats and cannot be compared or aggregated easily with other sources. The Landslide Database Interoperability Project being coordinated by Geoscience Australia is a first step toward addressing this information gap (Osuchowski 2006).

Additionally, throughout Australia geotechnical investigations are occurring as routine activities performed by councils within their development approval processes. The councils retain a great deal of detailed information on the landslides in their municipalities, although the data are difficult to retrieve once they have been lodged with a regulator. There is seldom incorporation of, or reference to, these geotechnical reports in landslide databases and landslide information is rarely synthesised across multiple jurisdictions. If this information was made easily accessible to those who undertake risk analysis, it could significantly improve the availability of the basic knowledge required to assess landslide frequency and occurrence. Additionally, successive investigations in one vicinity would be able to build on previous research.

Landslide Susceptibilty Mapping

The distribution of landslides in the Australian landscape is not well known. There has never been a national landslide susceptibility or hazard (likelihood) mapping programme, and only limited nationwide studies of landslides have been conducted.

It is difficult to assess landslide susceptibility on a national scale, because landslides are dependent on the interaction of localised conditions, and methods to overcome the data limitations are still being developed. Landslide mapping, when conducted, generally occurs only on a site-specific scale and is performed by geotechnical consultants for purposes of zoning, building infrastructure or applying for development approvals.

The regional susceptibility mapping of areas prone to landslides is not commonly undertaken in Australia. Without regional mapping, it is difficult for those with regulatory responsibilities to be aware of any landslide risks within their jurisdictions and target areas for detailed mapping. Examples are provided in Ezzy and Mazengarb (2007), Miner and Dalhaus (2006), and in a Victorian Government report regarding the Alpine Resorts Planning Scheme (DSE 2007a).

First-pass landslide susceptibility maps are needed, particularly across areas with known histories of landslide occurrence. The limitations of the mapping and the levels of accuracy need to be made explicit on such maps.

The availability of relevant datasets, such as geomorphology at scales of 1:25,000 or better, is highly variable throughout the country, even when considering the major urban areas. High-resolution data are essential for undertaking susceptibility, hazard and risk analyses in localised regions.

Fundamental research directed at better understanding landslide processes in the Australian setting is currently very limited. There are also significant geomorphic research gaps which include measuring the age of Australia's landscape and developing landscape evolution models which can contribute significantly to better appreciation of slope-forming processes and their associated process rates.

Landslide Hazard Mapping

The primary constraint to hazard mapping is a lack of good inventory maps and validated inventory databases, in addition to resource constraints.

There is a need for systematic and standardised landslide hazard assessments throughout the country, in order to assist stakeholders, such as regulators, to be aware of landslide hazards and to make informed land use decisions. Emergency management agencies would also benefit from acquiring a more technical understanding of landslide hazard areas to inform the development of emergency action plans.

Determining temporal probability is often not possible, because of the absence of historical landslide records which can be related to the historical records of triggering events, the scarcity of input data, or the insufficient length of historical records of triggering events (van

Westen and others 2005). Determining the cumulative effects of human influence is difficult, particularly in urbanised areas susceptible to landslides.

Ongoing analysis of the influence of triggering factors, such as rainfall events, on representative and problematic landslides in Australia is needed. Monitoring programmes, including the use of near real-time technologies, can provide information on the relationships of landslide movements to triggers. This is important if public safety warning systems are to be developed as part of risk management and disaster plans.

At the local and regional levels, there is a need for research programmes that determine the relationships of contributing factors to landslide occurrence, magnitude–frequency rules and run-out limits for representative areas across Australia. As a strategic exercise, in the absence of national mapping strategies, this would provide context for site-specific investigations and other regional mapping exercises. Coupled with this aspect is the ongoing development of methods for implementation in applications such as landslide zoning.

Influence of Climate Change

The influence of climate change on landslides in Australia is not being specifically addressed by any agency. The effects of climate change on the frequency and intensity of rainfall triggers, as well as the impacts of rising sea level, need research.

Further research is also needed on the differences between a changing climate and 'climate change', climate mechanisms which deliver high-risk periods, and ways in which human activities complicate the interactions of climate cycles.

This includes better understanding the relationships between fossil landslides and the climate at the time of failure. This would allow a picture of prehistoric landslides and their causes to be developed, analogous to the process of identifying and dating fault scarps formed during

The aftermath of a debris flow damaging a resort on Magnetic Island, January 1998
Photo courtesy: Geoscience Australia/Marion Leiba.

State Emergency Service volunteers involved in rescue efforts at a fatal landslide at Thredbo, New South Wales, July 1997
Photo courtesy: Geoscience Australia.

large prehistoric earthquakes. This is important, as decadal cycles influence the activity of deep-seated failures and raise issues with likelihood prediction.

Roles and Responsibilities

The majority of landslide practitioners in Australia are in the private sector; considerably smaller numbers are in universities or state government agencies. The roles and responsibilities of those involved in managing parts of landslide risk are described below.

Australian Government

The Australian Government's overarching goal in the management of landslide risk is to ensure the development of safer communities. The Australian Government offers some financial assistance for landslide studies and landslide mitigation measures, through its funding programmes aimed at reducing the risk of natural disasters. It maintains the Australian Landslide Database and provides overarching emergency management and land use planning guidelines.

The Australian Government plays a role in raising awareness of landslide hazard though education and training programmes (EMA 2001a; EMA 2001b), and contributes to innovative research to assist the mining industry through the development of models which assess the geotechnical stability of artificial slopes.

The Australian Government also underpins and coordinates a number of intergovernmental organisations and groups, particularly those directed to planning and building codes, such as the Development Assessment Forum.

State and Territory Governments

Legislation varies across states and territories in Australia; some have stronger legislative requirements than others. Current Australian legislative controls are outlined in ABCB (2006), Leventhal and Kotze (in press) and Tefler (1988).

State and territory governments differ in their approaches to managing landside hazards. Some have accepted the AGS (2007) predecessor *Landslide Risk Management Concepts and Guidelines* (AGS 2000) as an industry reference paper within legislation. All play an important role in strengthening partnerships with local governments, and in encouraging and supporting them to undertake disaster risk assessments and mitigation measures.

All state and territory governments, with the exception of the Tasmanian Government, delegate responsibility to their local governments. Mineral Resources Tasmania is the only state government agency that undertakes regional mapping of landslides, maintains a state-wide landslide database, and provides landslide information to the public. Mapping is generally undertaken by the private sector in other jurisdictions.

Planning agencies in each state and territory develop coastal policies and landslide or erosion policies (EMA 2001a; DAF 2007). However, it is believed that some erosion policies do not specifically relate to landslide hazard, which can result in confusion among land owners and members of the general public. One example is the Erosion Management Overlay in Victoria (Golder Associates 2004; DSE 2007b).

Road and rail transport agencies have a responsibility to protect road and rail infrastructure against landslides and to ensure construction does not increase landslide hazard. They do this by liaising strongly with geotechnical consultants.

Local Government

The majority of mitigation and development controls for slope management are achieved at the local government level (Leventhal and Kotze in press). Most landslide work is also undertaken at this level, with the private sector providing advice and support.

Local governments have principal responsibility for systematically taking proper account of risk assessments in land use planning to reduce landslide risk. Local government agencies are responsible for reducing landslide losses using the best information available (COAG 2004).

Zoning and planning schemes across local government are variable across jurisdictions within each state and territory. Some local governments designate 'landslide hazard zones' which control development within their jurisdictions, while others have not recognised or planned for landslide-related risk (Leventhal and Kotze in press).

While guidance is provided by the Development Assessment Forum (DAF 2007), systematic policy implementation to address landslide hazard is rare across local governments.

Local governments also have a regulatory responsibility, and regulatory approaches vary widely. There are no requirements for building constructions with the capability to withstand a landslide; regulatory control is currently directed toward preventing exposure to landslides (Leventhal and Kotze in press). A number of parties are involved in the landslide risk management process, although pragmatically the regulator sets the tolerable risk levels. Regulators need to appreciate the complexities of landslide risk analysis in order to ascertain the rigour of any geotechnical landslide reports upon which they base their decisions. The regulator is best placed to act in the interests of the community with respect to landslide hazard, particularly for matters relating to transfer of risk upon sale of properties.

Industry, Coordinating Groups, Professional Bodies and Research Institutions

There are a number of professional bodies and industry bodies that play an advocacy and leadership role in landslide risk management. Most function at a national scale: for example, Engineers Australia and the Australian Building Codes Board. The National Engineering Registration Board recognised the challenges some regulators face and developed a 'specific area of practice' within the National Professional Engineering Register for landslide risk management.

Professional societies help to integrate the engineering and geotechnical science into decision making. They serve as conduits of information from researchers to practitioners. They are the source of codes and handbooks

A fatal landslide at Paluma Road, north of Townsville, Queensland, March 1997
Photo courtesy: Geoscience Australia/Marion Leiba.

which provide best practice guidance, and some also offer professional training. For example, the Australian Building Codes Board identified that construction in areas prone to potential landslide hazard was an issue that requires consistent uniform guidance across the nation, and published a non-mandatory guideline (ABCB 2006) to provide advice on this matter.

Numerous geotechnical and engineering consulting companies are involved in landslide hazard and risk assessment on behalf of government and non-government agencies. Many conduct landslide research, develop landslide mapping and monitoring techniques and maintain their own landslide inventories. Engineering geologists, geotechnical engineers and building professionals provide geotechnical advice to government, business, industry and private property owners. They make a significant contribution to the development of methods, for example in undertaking landslide risk assessments for property developers and addressing legal liability in slope stability assessments.

The University of Wollongong undertakes research encompassing landslide risk management, the development of GIS-based mapping techniques (Flentje and others 2007) and continuous real-time monitoring. The monitoring stations are facilitating quantitative landslide frequency assessments and providing real-time warning capabilities. The university works cooperatively with the Wollongong City Council, the local office of the New South Wales Roads and Traffic Authority and RailCorp. It is known that other universities undertake landslide research programmes although it is believed that this occurs on an ad hoc basis.

Property Developers

Developers are required to prepare development applications which address councils' provisions relating to development in areas susceptible to landslides. The developer is required to provide a geotechnical assessment of the site which demonstrates that the development proposal takes into account appropriate mitigation techniques, and to seek advice from qualified engineering geologists and geotechnical engineers on site slope instability as part of that assessment. A qualified geotechnical professional may assess the reliability of these reports in landslide-prone areas.

AGS (2000; 2007a-e) provides a means for owners, occupiers, regulators and insurers to be aware of the risks involved in construction of all manner of developments, from residential developments to infrastructure critical to community safety, and to manage such risks (Leventhal and Walker 2005).

General Community

Members of the general community have a responsibility to be aware of how their activities might impact upon their own property and that of their neighbours. Valuable information for the general public is contained within the GeoGuides (AGS 2007e).

While it is possible for marginal land to be developed within tolerable levels of risk, meeting any imposed maintenance requirements is the responsibility of the home owner. The risk level one owner or occupier is prepared to accept may not be accepted by another, and there may be transfer of risk issues and issues of nondisclosure during the sale of affected property. The regulation of this is legally and pragmatically challenging and legal intervention commonly results in local governments shouldering this liability.

Individuals who intend to purchase or occupy homes on, or in proximity to, sloping land or a cliff should contact their local council for guidance on slope instability or development issues. Individuals should seek professional advice if they are concerned about slope stability in their area, and should seek any landslide mapping information that may be detailed enough for site specific analysis from the council.

Conclusions

Landslides in Australia are predominantly triggered by an increase in pore water pressure from intense short-period or prolonged rainfall. Human activity can impact both positively and negatively on the occurrence of landslides. The regular occurrence of landslides across Australia makes it difficult to estimate their cumulative impact in socioeconomic terms, as costs are distributed, misreported or not documented.

Modelling the likelihood of landslides requires each physical process to be approached differently and analysed separately, in any level of risk analysis. The information and approach necessary for effective modelling depends on the scale of investigation and requires data primarily on historic landslide occurrences as well as on site setting and trigger factors. To model consequence requires knowledge of the type of landslide and the elements at risk, and an understanding of how vulnerability varies with each element at risk.

The adoption of best practice guidelines and methods is an important step in minimising and managing landslide impacts. Further work in the areas of landslide inventories, including reliable maintenance of landslide databases and model development, is important. There is also a need to contribute to management of landslide risk at the technical level through support for nationwide landslide susceptibility mapping at the scale of regional or local government areas.

The management of landslide risk is important for all levels of government, non-government agencies and groups and the community. However, local governments have a major statutory responsibility for managing landslide risk and private industry plays a fundamental role in this process. Skills shortages and resource limitations are primary constraints in furthering landslide research.

Residential development along a 22 metre high coastal cliff-top subject to ongoing erosion at North Bondi, New South Wales
Photo courtesy: Greg Kotze/captured in 2005.