6 Landslide hazards

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6.1 Introduction

Landslides are naturally occurring phenomena in every environment on Earth, including the tropics, the temperate regions and the high latitudes, and in the oceans. Unfortunately, this ubiquitous natural process represents a substantial hazard to humans because people and structures have a surprisingly low capacity to withstand the forces generated by mobile soil and/or rock. In consequence, there is a long recorded history of landslide disasters – for example, Nihon Shoki (the ancient chronicle of Japan), which was completed in the year AD 720, describes numerous landslides and failures associated with the Hakuho earthquake on 29 November AD 684, whilst the city of Helike in Greece is believed to have been submerged and destroyed as a result of a submarine landslide in 373 BC. Today, landslides continue to inflict a substantial economic and social toll, especially in mountainous, less developed countries, and there is a widely held but admittedly poorly quantified expert perception that the impacts associated with mass movements are increasing rapidly with time.

The term landslide is unfortunately something of a misnomer as many landslides do not in reality involve sliding. The word landslide is used to describe a range of processes that result in downward and outward movement of slope-forming material composed of rock, soil and artificial materials. In this context the term 'mass movement' might be preferable, but here the term landslide will be retained as it is in such common use in this context. In this chapter mass movements that are mostly formed from snow or ice are specifically excluded – these are discussed in Chapter 5.

Damaging landslides occur through a surprisingly wide range of magnitudes and invoke a large number of mechanisms. For example, the fall of a single piece of rock the size of a computer mouse can be enough to kill a person if it strikes them on the head at terminal velocity. On the other hand, the Seymareh landslide in the Zagros Mountains of Iran has a deposit with a volume of about 20 km^3, whilst some submarine landslides are now known to have a volume that may be as much as two orders of magnitude as large again. For this reason, landslide volumes are usually considered on a logarithmic scale. The wide range of landslide types is usually considered by classifying them according to the predominant material involved and the movement type (Table 6.1). A further refinement, which is important in the context of hazard causation, is to classify the landslides by movement rate as well. In general, rapid movement types are more likely to cause loss of life than are slow movements, whilst even slow rates of displacement (and low levels of total movement) can cause extensive damage to buildings and infrastructure.

Figure 6.1 presents the distribution of fatal landslides between January 2006 and December 2007 inclusive, based upon the Durham fatal landslide database (see Petley *et al*., 2005a). Care is needed in the interpretation of such a map as the inclusion specifically of fatal landslides (rather than all landslides or all landslides that impact upon people) biases the data in particular ways. Most importantly, the data are skewed towards less developed countries where the level of mitigation against landslides might be lower and where the density of vulnerable economic assets might also be small. Nonetheless, it is clear that the recorded landslides form very distinct clusters, most notably in the following locations:

1. Along the southern edge of the Himalayan mountain chain;
2. In Central China;
3. In SW India;
4. Along the western boundary of the Philippine Sea plate through Japan, Taiwan and the Philippines;
5. In central Indonesia, particularly on the island of Java;
6. In the Caribbean and Central Mexico;

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TABLE 6.1. *A simplifed classification scheme for the main types of landslide movements*

		Type of material		
		Rock	Engineering soils	
Type of movement			Coarse grained	Fine grained
Falls		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Slides	Rotational	Rock slump	Debris slump	Earth slump
	Translational	Rockslide	Debris slide	Earth slide
Lateral spreads		Rock spread	Debris spread	Earth spread
Flows		Rock flow	Debris flow	Earth flow
Complex slope movements (i.e. combinations of two or more types)				

After Varnes (1978)

7. On the western edge of the northern part of South America, especially in Colombia.

There is also a scattering of fatal landslides elsewhere, for example through Europe, the tropical parts of Africa and in North America. This distribution of intense fatal landslide activity reflects the juxtaposition of three key factors:

1. The occurrence of tectonic processes that in particular drive high rates of uplift and occasional seismic events;
2. The occurrence of high levels of precipitation, usually including both high annual precipitation totals and high short-term intensities;
3. The presence of a reasonably high population density.

Where one of these three factors is missing the occurrence of fatal landslides reduces markedly – thus for example Iran has a lower than expected landslide occurrence because of the absence of precipitation; Alaska has a lower than expected occurrence because of the absence of people; and Central Africa has a lower than expected occurrence because of the low levels of tectonic activity. A longer time-frame would change this picture slightly as landsliding in arid, tectonically active areas such as Iran is probably driven primarily by seismic activity with an additional input from low-frequency–high-magnitude rainfall events. Thus, if the data were collected over a sufficiently long period to capture a number of large seismic events in Iran then the maps would take on a slightly different appearance.

6.2 Landslide causes and triggers

Based upon the geomorphic distribution, it is unsurprising that the vast majority of landslides are triggered by one or more of three key factors: precipitation, seismicity or the action of humans. However, for these processes to be able to induce the landslide there must first have been a series of other processes that have acted to prepare the slope for failure. These processes, which are usually termed 'causes' as opposed to triggers, include the following.

6.2.1 Geological causes

Geological causes are factors that make the materials that form a slope susceptible to failure. Key causes include, for example, materials that are weak or that are weathered; materials with strong joint sets, especially where they are orientated in such a way that they allow sliding to occur; and material combinations that cause water to be retained.

6.2.2 Morphological causes

The most obvious morphological cause is the slope angle. The key parameter is the angle of the slope in comparison with the strength of the material. Thus, it is not a straightforward relationship in which steeper slopes are less stable – in Norway, for example, slopes formed from unweathered gneiss are able to form cliffs that can stand vertically to elevations of many hundreds of metres along the margins of fjords. On the other hand, quick clays close to the water's edge can fail at slope angles as low as 10° when disturbed. A further key morphological factor can be the concavity or convexity of the slope, which can serve to concentrate water in key locations. Finally, in many high mountain areas the loss of glacial ice leaves slopes unsupported and thus prone to failure, whilst in coastal environments the under-cutting of cliffs can lead to reductions in stability.

6.2.3 Physical causes

A third group of causes are related to physical processes. For example, a slope might be more likely to fail if the groundwater level has been elevated by previous prolonged rainfall or by snowmelt. Similarly, the loss of tree cover may make a slope far more susceptible to shallow landslides. In California, for example, shallow landslides that sometimes transition into destructive debris flows are a particular problem in the wet season following large forest fires.

FIGURE 6.1. Map showing the locations of fatal landslides in 2006 and 2007, as recorded in the Durham University Landslide Database. Each black dot represents a single fatal landslide.

6.2.4 Human causes

The final group of factors is centred around human activities that can destabilise a slope. Examples include the removal of forestry through logging or firewood collection; over-steepening of slopes through cutting for road construction or through quarrying; and the leakage of pipes or swimming pools. For example, in Nepal the occurrence of fatal landslides has increased markedly in recent years as a result of the construction of rural roads with inadequate levels of slope stabilisation and water management. Slopes that have been destabilised by the road building then fail during intense precipitation events associated with the summer monsoon, blocking the road and causing substantial and increasing levels of loss of life (Petley *et al*., 2007).

6.2.5 Causation vs. triggering

In most cases the final failure of a slope occurs as a result of a clear trigger. On a day-to-day basis the most common trigger is precipitation, sometimes supplemented by the effects of snowmelt. Precipitation serves to increase the pore pressures within a slope, reducing the resistance to movement. In temperate and cold environments this occurs primarily through increases in groundwater level. Thus, unless there has been a marked change in a causal factor as outlined above, landslides usually occur during precipitation that is low frequency–high magnitude, in terms of intensity and/or duration. However, if there has been a major change to the causal factors – for example, if there has been extensive recent deforestation – then extensive landsliding can occur in non-exceptional rainfall events.

Thus, from a human perspective it is clear that landslide hazard is associated with a complex range of interrelated factors, which can be conceptualised as a ‘chain of events’ (Figure 6.2). For the landslide disaster to occur there must be the juxtaposition of a number of causes plus the final trigger and the element at risk. From a hazard management perspective this can be helpful as the occurrence of the damaging landslide can be prevented through any one of a number of interventions, each of which addresses either a key cause, the trigger or the elements at risk (Figure 6.2). Of course this is a somewhat simplistic way to view landslide hazard reduction, but in the real world the level of hazard can often be reduced through a number of approaches. Thus, in Nepal, for example, in areas in which good quality engineering input is utilised the slope hazard can be reduced by using one or a combination of the following approaches:

1. Selecting an alignment for the road that avoids areas of known existing instability, or areas in which materials are known to be problematic (black schist often causes problems in humid tropical and subtropical environments for example), or areas with a slope angle greater than a pre-determined value;

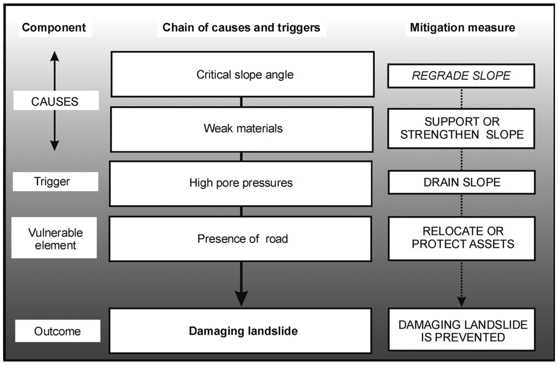

FIGURE 6.2. Conceptual diagram showing how the causes, a trigger and the existence of a vulnerable element conspire to create a slope accident. On the right, possible mitigating approaches are shown. Any one of these, applied properly, can prevent the accident from occurring.

2. Managing the water on the slope through the construction of effective drainage;
3. The construction of walls to support slopes that have been cut;
4. The planting of local vegetation species that can help to increase the strength of the soil or to draw down the water table. Vetiver grass (*Chrysopogon zizanioides*) is widely used in this capacity for example as it rapidly grows roots that extend to a depth of up to four metres.

Thus, key aspects of landslide hazard reduction are to identify and understand the causes; to identify and understand the triggering processes and the key thresholds at which they occur; and to try to ensure that human elements are not put at risk.

6.3 The role of geomorphology in landslide hazard management

Landslide management is a well-developed science, and where sufficient resources are available most small- to medium-sized landslides can be managed or mitigated if they have been identified and characterised properly and if sufficient resources are available. The management of landslides is a multi-disciplinary task, with key inputs from geotechnical engineers, engineering geologists, biologists, meteorologists, planners and others in addition to geomorphologists. Indeed, landslide management is rarely trusted to geomorphologists alone, instead the key role is to act as part of a multi-disciplinary team. The nature of the management of a landslide hazard depends to a large degree on the nature and timing of the movement, and whether the failure in question is a first time event or a reactivation of an existing landslide. However, geomorphology is a key aspect of all stages of the landslide management process.

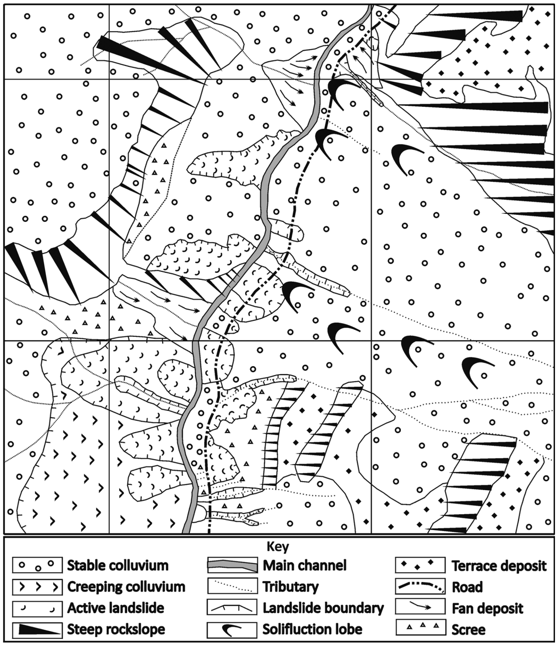

FIGURE 6.3. A terrain map used to identify the locations of existing landslides along the Arniko Highway in Nepal. The grid squares are 1 km.

6.4 Terrain mapping

A key aspect of landslide hazard management from a geomorphic perspective is that of terrain mapping. Terrain mapping, which is increasingly a key part of the early stages of infrastructure projects, especially in mountainous terrain and in areas affected by neotectonic processes, is most commonly used to identify areas of existing or past slope instability. In many cases, this provides a key input into route selection for roads, railway lines and in particular for pipelines. For example, route selection for the Dharan–Dhankuta highway in Nepal was undertaken primarily on the basis of geomorphological mapping (Brunsden *et al*., 1975). The value of this approach has been demonstrated by the remarkable stability of this road in comparison with similar projects for which this approach was not adopted (Hearn, 2002). Sometimes it is impossible to route the corridor away from areas with identified instability, in which case the terrain mapping is used as an input into more detailed geotechnical investigation. Terrain mapping is also often used as a first order hazard assessment technique, allowing the location of existing failures that might threaten an asset. For example, this approach was used to assess the likelihood of landslides along the access roads to Kathmandu in Nepal in the event of a large earthquake (Figure 6.3).

In recent years, the availability of high resolution digital aerial photography, satellite imagery, LiDAR data, and digital terrain models has allowed increasing levels of sophistication in terrain mapping. The development of increasingly sophisticated automated feature extraction will continue to enhance these capabilities. Despite this, terrain mapping is an under-used tool in infrastructure projects. Expensive failures, such as the reactivation of an ancient landslide that was clearly visible on aerial photographs at Ok Tedi in Papua New Guinea in 1984 (Griffiths *et al*., 2004), show that there are substantial advantages in the undertaking of good terrain mapping. The resultant legal case, which reached the Supreme Court of Papua New Guinea in 1989, was for approximately £575 million (Griffiths *et al*., 2004). The case was settled out of court.

The greatest weakness of terrain analysis continues to be the subjective nature of the process. Fookes and Dale (1992) examined six independent interpretations of the pre-failure condition of the Ok Tedi site described above, showing that even with highly skilled geomorphologists substantially different interpretations resulted. Similarly, when different analysts looked at identical aerial images of the site, surprisingly different interpretations resulted (Fookes *et al*., 1991). Nonetheless, terrain mapping remains a core tool in the development of infrastructure projects.

Brunsden (2002) advocated that terrain mapping should be the basis of a much more integrated geomorphological analysis of potential instability. He encouraged a move from an essentially two-dimensional analysis of landslides – i.e. the production of landslide maps – into a four-dimensional analysis that used geomorphological tools to understand the three-dimensional structure of an unstable slope, plus its development through time. Thus, for example, modern dating techniques can be used to understand the evolution of the slope, which can then be benchmarked against the increasingly high quality climatic and in some cases seismic histories that are now available. In consequence the relationship between movement and causal/ triggering factors can be elucidated, which gives an improved ability to understand future behaviour. This is becoming increasingly important in the context of climate change, which means that existing magnitude/frequency catalogues for triggering events may not be relevant.

6.5 Susceptibility analysis

The inherent subjectivity of terrain mapping has led to a multitude of attempts to develop more reliable, quantitative/semi-quantitative landslide hazard mapping techniques. The development of GIS has undoubtedly facilitated this approach as it hypothetically at least allows a consistent, high resolution approach to be applied to large areas. In all cases a simple algorithm is used to derive a score that indicates the susceptibility of a slope to failure. The simplest algorithms are based upon a small number of parameters (for example slope angle and material), and the parameters themselves are arranged in classes (e.g. slope angles of 0° to 5°, 5° to 15°, etc.). Summation is commonly used to derive an overall score that indicates the susceptibility to failure. In the most basic applications the score is determined on a slope by slope basis using a proforma that is completed by an operator. However, GIS-based approaches utilise algorithms that combine data from thematic layers. More complex systems utilise multiple input parameters and algorithms that are, for example, based upon empirical models of slope behaviour, such as the infinite slope equation and soil slope hydrology equations. In recent years, as processing power has increased, the use of probabilistic approaches, often based upon Monte Carlo simulations, has become popular.

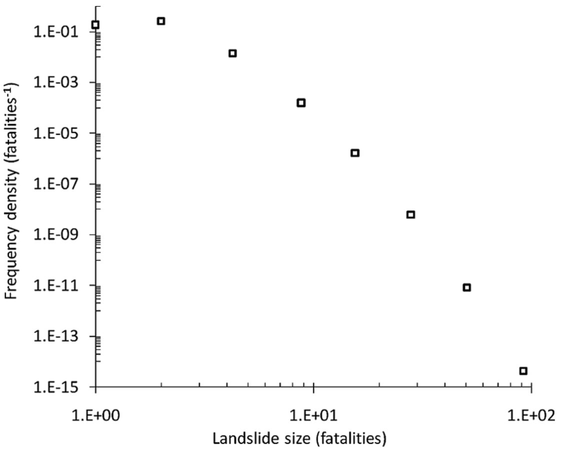

FIGURE 6.4. Landslide frequency (here represented by a frequency density function) plotted against magnitude (here represented by number of fatalities per event) for Nepal. (After Petley *et al*. 2007.)

Geomorphology plays a key role in all aspects of the development of susceptibility analyses. For example, geomorphologists have been at the cutting edge of the development of both the classification-based approach and the more quantitative analyses, and in the interpretation of their outcomes. Globally, the most commonly used approach is the CHASM model developed by Malcolm Anderson and colleagues at Bristol (e.g. Brooks *et al*., 2004) and subsequently applied in many different parts of the world. Furthermore, geomorphologists often implement the model runs and analyse the outcomes. However, serious questions about the reliability of this approach given the simplifications that are inherent in the construction of any algorithm, and in the input data, remain. The greatest concern with such analyses lies in the ability to verify or refute the outcomes. Thus, there is still much to do to improve the approach.

6.6 Hazard and stability analyses

In some cases, susceptibility models are developed to full hazard and even risk models. A hazard model requires that the frequency (i.e. probability) of occurrence is quantified and that the magnitude is also determined. In the case of landslides, magnitude generally refers both to the size of the landslide (i.e. the volume and surface area) and the rate of movement, as both are critical to the actual impact of the event. The development of magnitude–frequency relationships for landslides remains a fascinating area of research, not least because of the surprising similarities in these relationships between different areas and as a result of different triggers (see Malamud *et al*., 2004, for example). The cause of this consistent pattern of self-organisation, which is applicable to landslide losses as well as the landslides themselves (Figure 6.4) remains unclear, but represents an interesting potential input into hazard evaluation.

A key aspect of the evaluation of the frequency of landslides is the reconstruction of landslide chronologies using archival data. The principle is that our conventional scientific records are too short to provide a proper representation of the occurrence of landslides, and that the occurrence of landslides under environments that are different to the present can only be properly evaluated using long-term records. A range of approaches have been developed by the geomorphology community to allow this, and these continue to improve with time as, in particular, dating methods become better constrained. The use of long-term archive records of movement extracted from non-scientific reports is a key approach – for example, the relationship between movement and rainfall patterns for the Ventnor landslide on the Isle of Wight has been constrained using such a technique (Ibsen and Brunsden, 1996). Such datasets are limited by human records, which in a geomorphological sense are short. Extension of these records has been achieved using various dating techniques. For example, Borgatti and Soldati (2002) used carbon dating of wood entrained in landslide debris to establish the temporal occurrence of landslides in the Alps that could then be related to palaeoclimate reconstructions for the Holocene, establishing the link between climate and landslides. Whilst being very powerful, such techniques are expensive and time-consuming as many dates are required. Furthermore, uncertainties remain as landslides tend to be triggered by weather events whereas palaeoclimate data provide an indication of climate. Similar studies using other dating

FIGURE 6.5. The town of Taihape in North Island, New Zealand, which is built upon a slow moving earthflow. Monitoring is used to ensure that the town remains secure.

techniques have been used to establish landslide chronologies, including lichenometry and dendrochronology (see Lang, 1999, for a detailed review). In the last few years the availability of cosmogenic isotope dating, which allows the time of unroofing of rock surfaces to be established, has allowed the dating of large rock avalanches and rockfalls (Mitchell *et al*., 2007). There is increasing interest in the use of this technique for the determination of the chronology of large earthquakes using rock avalanches as the indicator of the seismic event (Korup *et al*., 2004).

Estimating the likely volume or surface area of a potential failure remains very troublesome, especially if runout distance is to be included. Rates of movement are generally analysed using numerical models. This is easier for a single landslide in a site that is well characterised, but is very difficult where hazard is being assessed for a larger area. Even in the case of a well-constrained specific site, reliable modelling of known failures still requires that the model is tuned with specific parameters that are not physically representative. Thus, predictive modelling has a poor level of reliability.

6.7 Monitoring, behaviour prediction and warning systems

In many parts of the world, people live on or are affected by landslides that cannot be easily mitigated. Examples include settlements that are located on slow moving or inactive landslides (the towns of Ventnor in the UK and Taihape in New Zealand (Figure 6.5) are examples where this is the case); transportation routes that cross landslides (for example the Ashcroft landslides in Canada), and landslides that threaten other economic assets, such as reservoir bank failures that imperil dams through displacement waves. Frequently the landslides are either too large or too numerous to be effectively mitigated and the assets cannot be relocated. In this case an increasingly common approach to the management of the slope hazards is the use of monitoring systems, some of which are used to provide warnings.

Warning systems over large areas tend to be based upon measurement and analysis of the thresholds at which potential triggers start to induce landslide movement. Considerable work has been undertaken in particular on the development of thresholds of rainfall for landslide activation. Generally the approach used is to examine rainfall events that are known to have caused landslides and to compare them with events in which no landslides have occurred. Usually, the best relationships are found by looking at a combination of medium-term precipitation (perhaps rainfall total over the previous month) and short-term rainfall (over the last few hours). Thus, the threshold for movement in terms of short-term rainfall is usually lower if the previous few days have been wet than if they have been dry. Such approaches are the basis of warning systems in a number of places – for example Japan and Hong Kong both operate large-scale systems for landslide warning. However, implementation of such systems is rather complex as rainfall is very spatially variable. In Hong Kong, which has a surface area of just 1,092 km^2, the warning system is based upon 110 rain gauges plus the use of a Doppler rain radar system. Even then, the system is operated with caveats, in particular that unexpected intense rainfall, perhaps associated with a rapidly developing convective system, can induce landslides before a warning can be issued. Nonetheless, the development of appropriate rainfall thresholds has been and continues to be a key task for geomorphologists. In Malaysia for example, which has a surface area of about 330,000 km^2, there are plans to ultimately create a nationwide slope warning system based upon rainfall thresholds, although this will take years to implement and will be expensive to maintain. Similar warning systems for earthquake-induced slope hazards are in their infancy, but the new Taiwan High Speed Rail Line has earthquake acceleration sensors mounted along the length of the track that automatically stop the trains if ground accelerations exceed 40 gals, partly to ensure that trains do not hit failures induced in the earthworks alongside the track. Given the low shaking threshold, it can be hoped that in the event of a large earthquake the sensors would initiate the stopping sequence before the main earthquake waves arrive at the track, and thus before any embankment failures, occurred. However, such systems have rarely been tested by large earthquakes, so we wait to see their effectiveness.

Warning systems on individual slopes generally take a quite different approach, in this case being based upon the detection of landslide movement. Three approaches are generally adopted:

1. Sensors, often based upon vibration or using echo sounders to detect changes in sediment volume, are placed in the path along which a landslide is expected to move, allowing a warning signal to be issued. Such warning systems generally provide a warning over only a very short period (seconds to minutes), allowing emergency evacuations along pre-determined routes or the closure of key transportation routes such as roads. Geomorphology plays a key role in all aspects of the development of such systems, including the identification of hazardous slopes that require warning systems; the determination of the optimum monitoring locations and sensor type; the selection of appropriate thresholds; and the determination of safe escape routes and zones. Such warning systems have proven to be successful in

many locations – for example, the town of Funes in the Dolomite mountains of northern Italy has been protected for over a decade against catastrophic debris flows using such a system (Petley *et al*., 2005b).

2. An alternative approach is to measure the conditions in the slope that are considered likely to trigger failure. In most cases this is based upon a calculation of the stability of the slope using a static equilibrium (i.e. factor of safety) calculation. This allows the critical groundwater level (or pressure condition) at which failure is considered likely to be determined. This is often backed up with records of movement, analysed in conjunction with measurements or models of the groundwater conditions at the time. Monitoring of the groundwater level using piezometers then allows a warning to be made when the groundwater approaches this critical depth.
3. The final, increasingly popular, approach is to detect the early (precursory) stages of landslide movement, generally using movement sensors. The rationale is that catastrophic failure is usually presaged by a period of accelerating movements of the slope. Thus, once a predetermined movement rate is reached, or when a specific pattern of acceleration is observed, a warning is sounded. Early systems focussed upon the use of inclinometers located in boreholes, which measure the movement between the base of the landslide and the underlying bed, or extensometers that measure movement across the back scar at the landslide head. Increasingly, however, technologically based approaches are being adopted, typically using robotised theodolites in conjunction with reflective targets located on the landslide body (Petley *et al*., 2005b) or high resolution differential GPS receivers located on the landslide mass (Tagliavini *et al*., 2007). These approaches are proving capable of providing warnings, and also have the advantage of generating detailed datasets on the movement patterns of the landslide that allows a better understanding of its dynamics. A series of new experimental approaches are also being developed, most notably slope radar, which is increasingly being used to provide warnings on large open-cast pit slopes, and satellite-based radar interferometry (InSAR) (Catani *et al*., 2005). The latter shows some potential but remains problematic, not least because displacement–time plots generally have an unrealistic linear trend, which suggests that crucial elements of movement are not being resolved.

A key challenge for the geomorphological community is the development of enhanced understanding of warning thresholds and the development of new techniques for the analysis of movement patterns. In particular, we still understand precursory movement patterns very poorly. An even greater challenge is that of behaviour prediction – i.e. can we determine the likely future movement of a landslide? Generally such problems are associated with large mass, slow moving movements that seem to have the potential to move rapidly. The slow movement implies a factor of safety very close to unity, so increased movement often seems very possible. An example is the Ventnor landslide on the Isle of Wight in southern England. This landslide has built upon it a town with a permanent population of 7,000 people and economic assets with a replacement cost of over £150 million. The landslide moves continually at a rate of a few millimetres to centimetres per annum, and the geomorphology evolves as a result. Opinion remains divided as to whether the slope is likely to evolve into a large-scale, rapid failure and if so, under what circumstances. However, Carey *et al*. (2007) used a combination of geomorphological analysis, interpretation of movement and piezometer data, and novel laboratory testing to examine the mechanisms of movement and thus to forecast likely behaviour, suggesting that a very rapid failure event is unlikely. Such approaches will increasingly represent a frontier of landslide research that builds upon the availability of good-quality, real-time movement data and, increasingly, models that reliably represent the full range of processes that occur within a slope.

6.8 Secondary hazards and sediment production

Landslides are frequently considered to be secondary hazards associated with a primary event such as a typhoon or an earthquake. However, it is increasingly clear that landslides generate their own set of comparatively poorly understood secondary hazards, most notably dam-break floods and tsunamis. The former was strongly demonstrated by the 2008 Wenchuan earthquake in Sichuan province in China, which induced a very large number of landslides that caused catastrophic damage – for example, the town of Beichuan was almost completely destroyed by two rock slope large failures. In the aftermath of the earthquake, however, there was great concern associated with the existence of 44 valley-blocking landslides, each of which had the capacity to cause a substantial and very destructive dam-break flood. The mitigation of such sites requires a high level of input from geomorphologists, most notably through:

1. The identification of sites in which there is high potential for the occurrence of valley-blocking landslides, most notably through terrain analysis (see above);
2. The analysis of the dynamics of a potential dam-break flood. Two key approaches are used: first, using

statistical relationships derived from previous events; and second, through flood modelling. In both cases information on the dimensional and material properties of the dam is critical;

3. The identification of safe locations for populations downstream that need to be relocated;
4. The design of safe mitigation measures, most notably the construction of a spillway to safely drain the lake.

In the case of Wenchuan, the authorities successfully drained all of the dangerous landslide lakes without the reported loss of a single life. However, the experience has caused many other earthquake-prone countries to reflect upon their own capabilities in this area. It is likely that there will need to be considerable investment in this field to allow a repeat of the Chinese achievements elsewhere.

The further substantial secondary hazard is that of the generation of a tsunami from a terrestrial or a submarine landslide. Here the threat is very real, as a number of well-documented cases demonstrate (Bardet *et al*., 2003). Unfortunately, the discussion of these hazards is sometimes sidetracked by over-blown descriptions of extreme landslide events for which there is no real physical evidence, in which single landslides are postulated as having the potential to generate tsunamis that could devastate whole ocean basins. Although such scenarios have little or no scientific credibility, the potential for serious localised impacts of large landslides into water bodies is well established. For example, in 1997 a tsunami associated with a $Mw = 7.0$ earthquake in Papua New Guinea struck the Sissano Lagoon, killing over 1,000 people. It is now clear that the source of this tsunami was a submarine slump triggered by the earthquake (Lynett *et al*., 2003). Currently, our understanding of the likelihood of such tsunamis is comparatively poor, not least because they are high magnitude but low frequency events. Considerable work is now being undertaken both to model the occurrence of such events and to map and date deposits left by them.

The 1999 Chi-Chi earthquake in Taiwan probably represents the most intensely studied landslide event on record (e.g. Chang *et al*., 2007). One aspect of these landslides that has been particularly interesting is the emphasis placed on understanding the ways in which the mass failures contribute to the erosional mass balance of tectonically active mountain chains (Lin *et al*., 2006). There have been two key components of this work. First, considerable effort has been expended in trying to understand how patterns of landsliding evolve in the aftermath of large earthquakes. In Taiwan it has been clear in a number of catchments that whilst the number of landslides associated with the initial earthquake is high, the number increases dramatically in the first extreme rainfall event after the temblor. In many catchments the number of landslides more than doubled. This of course has profound implications for hazard management in the aftermath of the earthquake – in Taiwan the Central Cross Island Highway, which is the main arterial route across the Central Mountain chain, has been repeatedly destroyed by landslides in the aftermath of the earthquake, at considerable cost. Nine years after the earthquake the occurrence of landslides is still well above the background level. Similar effects have been noted elsewhere (Keefer, 1994), but considerable further work is required to understand this process properly.

A linked issue is that of sediment mobility. The landslides triggered by large events can release huge quantities of sediment into the fluvial system. At the same time however large valley-blocking landslides can cause sediment to be deposited and stored within the channel. Understanding the interaction between these two processes, and their relationship to periods that are not affected by recent large events, is a key aspect of work in geomorphology. In the case of Taiwan, sediment transport increased dramatically in the aftermath of the earthquake, especially during large flood events. The rivers responded by aggrading – in places the river bed level has increased by as much as 30 m. Dadson *et al*. (2003) demonstrated that across Taiwan as a whole there is a correlation between seismic moment (i.e. earthquake energy release) and sediment production, presumably as a result of the occurrence of landslides. These variations in sediment release and transportation associated with earthquakes have important implications for the understanding of the evolution of hazards in affected areas – in the Tachia River Valley in Taiwan the landslides associated with the Chi-Chi earthquake and the subsequent sediment disasters are estimated to have cost a total of about US$968 million (Table 6.2).

TABLE 6.2. *Estimated costs of landslide and sediment induced damage in the aftermath of the 1999 Chi-Chi earthquake*

Item	Cost (US dollars)
Repairs to hydroelectric power infrastructure	$300 million
Additional power generation costs	$320 million
Initial road repairs	$53 million
Additional transportation costs for agriculture	$95 million
Estimated costs to rebuild Central Cross Island Highway	$200 million
Total	$968 million

6.9 Conclusions

Landsliding is a natural geomorphological process that acts primarily to balance uplift. Human activities exacerbate this situation considerably, increasing the spatial density and temporal frequency of failures. As such, landslides represent a hazard in all inhabited areas with slopes. Geomorphologists play a key role in the management of these hazards. Indeed, in recent years many UK-based engineering consultants have formed geomorphology units specifically to make use of the expertise that geomorphologists can bring to infrastructure projects in potentially unstable areas. However, many challenges remain, not least to gain a better understanding of the mechanisms of landslides in mountainous, tropical environments and to find effective ways to manage landslides in less developed countries.

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