PART 1

CONCEPTUAL MODELS IN APPROACHING LANDSLIDE RISK

2

The Nature of Landslide Hazard Impact

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2.1 Introduction

Landsliding is one of the many natural processes that shape the surface of the earth. It is only when landslides threaten mankind that they represent a hazard. Landslides belong to a much broader group of slope processes referred to as mass movement. The definition of mass movement includes all those processes that involve the outward or downward movement of slope-forming material under the influence of gravity. Some mass movement processes, such as soil creep, are almost imperceptibly slow and diffuse while others, such as landslides, are capable of moving at high velocity, are discrete, and have clearly identifiable boundaries, often in the form of shear surfaces (Crozier, 1999a).

Landslides are a manifestation of slope instability. This chapter discusses the stability of slopes, the factors that promote instability and the adverse effects that landslides can have on human well-being, land and livelihood. In particular, it identifies those aspects of landslides that make them hazardous and analyses the vulnerability of elements at risk in the face of landslide activity.

2.2 Slope Stability Considerations

Because of the destructive potential of landslides, scientists and engineers have long tried to identify the conditions of a slope that give rise to landsliding and in particular to determine how readily the slope may fail, that is, the 'stability' of the slope. Thus 'slope stability' and its corollary 'slope instability' are defined as the propensity for a slope to undergo morphologically and structurally disruptive landslide processes.

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Slow, distributed forms of mass movement such as soil creep are generally considered not sufficiently disruptive to be included in this definition. From a hazard and engineering perspective, assessments of slope stability are generally intended to apply to periods ranging from days to decades, or in some cases to specified periods relating to the design-life of a potentially affected structure. However, slope stability may also be treated as a factor in landform evolution and therefore its significance in this role has to be measured over much longer time scales (Cendrero and Dramis, 1996; Schmidt and Preston, 1999).

In every slope, there are stresses that tend to promote downslope movement of material (shear stress) and opposing stresses that tend to resist movement (shear strength). In order to assess the degree of stability, these stresses can be calculated for a known or assumed failure surface within the slope and compared to provide a factor of safety (defined as the ratio of shear strength to shear stress). In a static slope, shear strength exceeds shear stress and the factor of safety is greater than 1.0, whereas, for slopes on the point of movement, shear strength is just balanced by shear stress and the factor of safety is assumed to be 1.0 (Selby, 1993).

While engineering codes of practice may specify a particular factor of safety to be achieved for completed earthworks, there are limitations to this measure of stability. Consider for example two slopes (A and B) that have the same factor of safety but that have large absolute differences in excess strength (i.e. strength minus shear stress). Let us assume that the strength to stress ratio, in unspecified stress units for a slope (A) is 400/200 and for a slope (B) is 200/100; thus both slopes yield a factor of safety of 2.0. However, slope (A) has an excess strength of 200 units while slope (B) has an excess strength of only 100 units. As excess strength is the quantity that must be entirely reduced (by reduction in strength or increase in shear stress) in order to produce failure, it represents the inherent stability of the slope or, in other words, the 'margin of stability' against failure. Thus spatial differences in inherent stability are better represented by excess strength than by the factor of safety. Instability in its broadest sense, however, is determined not only by the margin of stability of the existing slope but also by the magnitude and frequency of (external) destabilizing forces acting on the slope that are capable of reducing that margin and initiating landslides. Defined in this way, slope stability/instability is akin to the concept of 'susceptibility' (see Chapter 1).

Slopes can therefore be viewed as existing at various points along a stability spectrum ranging from high margins of stability with low probabilities of failure at one end, to actively failing slopes, with no margin of stability, at the other (Figure 2.1). It useful to define three theoretical stability states along this spectrum, based on the ability of dynamic external forces to produce failure (Crozier, 1989). First is the 'stable state', defined as slopes with a margin of stability which is sufficiently high to withstand the action of all natural dynamic destabilizing forces likely to be imposed under the current environmental/geomorphic regime. Second is the 'marginally stable state', represented by static slopes, not currently undergoing failure, but susceptible to failure at any time that dynamic external forces exceed a certain threshold. Third is the 'actively unstable state', represented by slopes with a margin of stability close to zero and which undergo continuous or intermittent movement (Figure 2.2).

The margin of stability is thus a measure of slope sensitivity to destabilizing factors and, together with an assessment of the potential effect of destabilizing factors affecting

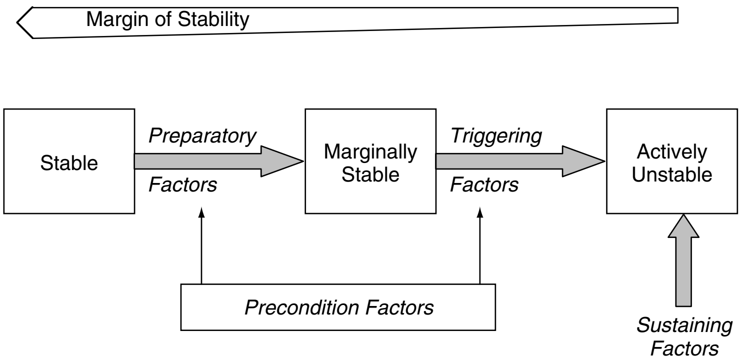

Figure 2.1 *Stability states and destabilizing factors (based on Crozier, 1989)*

Figure 2.2 *Actively unstable slopes, subject to deep-seated earthflows, Poverty Bay, New Zealand (photo by Ministry of Works, New Zealand)*

the slope, provides a measure of susceptibility/instability. In turn, an understanding and quantification of the relationship between the margin of stability and the frequency and magnitude of dynamic destabilizing factors provides one way of determining the probability of landslide occurrence. Ultimately, the probability of failure together with its magnitude provides a measure of landslide hazard.

Factors promoting slope instability are important to consider. The concept of three stability states offers a useful framework for understanding the causes and development of instability. In this context four groups of factors promoting instability ('destabilizing factors') can be identified on the basis of function (Figure 2.1).

Precondition (predisposing) factors are static, inherent factors which not only influence the margin of stability but more importantly in this context act as catalysts to allow other dynamic destabilizing factors to operate more effectively. For example, slope materials that lose strength more readily than others in the presence of water predispose the slope to failure during a rainstorm; or a particular orientation of rock structure may enhance the destabilizing effects of undercutting.

Preparatory factors are dynamic factors that by definition reduce the margin of stability in a slope over time without actually initiating movement. Hence, facilitated by preconditions, they are responsible for shifting a slope from a 'stable' to a 'marginally stable' state. Some factors, such as reduction in strength by weathering (Chandler, 1972), climate change (Dehn *et al*., 2000), and tectonic uplift (Shroder and Bishop, 1998), operate over long periods of geomorphic time whereas others may be effective in shorter time periods, for example slope oversteepening by erosional activity (Preston, 2000), deforestation (Schmidt *et al*., 2001), or slope disturbance by human activity (Rybár, 1997).

Triggering factors are those factors that initiate movement, that is, shift the slope from a 'marginally stable' to an 'actively unstable' state. The most common triggering factors are intense rainstorms, prolonged periods of wet weather or rapid snowmelt, seismic shaking and slope undercutting. Thus, if a slope is in a state of marginal stability it is possible to recognize a threshold value for the triggering factor that is responsible for initiating movement. The common triggering factors are usually external forces imposed on the slope and the initiating thresholds are thus referred to as extrinsic thresholds (Schumm, 1979). In certain instances, however, movement may be initiated in the absence of an identifiable external triggering force, and therefore it is assumed that some intrinsic threshold has been surpassed within the slope. For example, the Mount Cook rock avalanche from New Zealand's highest mountain in 1991 appears to have been triggered in this way (McSaveney, 2002). For this event it is suggested that gradual weakening of the rock mass, perhaps by mechanical weathering or dilation from unloading by continual erosion, lowered the rock mass strength below the prevailing gravitationally induced stress, allowing failure to occur.

In most cases, however, an extrinsic triggering threshold for landslide occurrence is identifiable and presents two useful opportunities for hazard estimation. The first opportunity recognizes that the triggering threshold varies with the inherent stability of the terrain. Thus spatial differences in the value of triggering thresholds can provide a relative measure of the geographic distribution of terrain susceptibility to landslide occurrence (Crozier, 1989; Glade, 1998). The second opportunity is that, having identified the triggering threshold for a given terrain, the triggering value may be used to determine the frequency of occurrence of landslide-generating conditions by reference, for example, to the seismic or climatic record for the region (Glade *et al*., 2000; Brooks *et al*., 2004). The advantage of this approach over determination of frequency from the historical inventory of landsliding is that climate records are usually much longer and more reliable than historical landslide records. In addition, these thresholds can be used for warning systems and forecasting of landslide activity (Crozier, 1999b).

While triggering threshold analysis has many advantages over other approaches for determining probability of occurrence for hazard estimation, there are two components of the analysis which need particular attention. First, it is essential that the threshold analysis is not based solely on values of the initiating agent that occur during landslide initiation. These may be in excess of the minimum triggering value and the computed frequencies would thus underestimate the true frequencies. Second, it is clear that in some situations the triggering threshold for a given terrain is not a constant but varies temporally as a result of landslide occurrence. As susceptible material is successively removed from hillslopes there is a residual strengthening of the terrain and the triggering threshold rises. This phenomenon is referred to as 'event resistance' (Crozier and Preston, 1999). A similar phenomenon can be observed with debris-flow occurrence. The activation of debris flows depends not only on the magnitude of the triggering event but also on the availability of transportable material. For example, if all source material is removed by a rainfall-triggered debris flow, further rainstorms of the same magnitude are unlikely to generate flows. Triggering thresholds can thus also be seen as a function of the time required to establish a critical volume of rock debris in the source area (Glade, 2004). The implication of sediment availability/removal and event resistance for hazard estimation is that historically derived magnitude–frequency relationships may not always be a reliable measure of future activity.

Sustaining factors are those that dictate the behaviour of 'actively unstable' slopes, for example duration, rate and form of movement. While some of these may be dynamic external factors such as rainfall, others may relate to the progressive state of landslide movement or the terrain encountered in the landslide path.

2.3 Landslide Types

The range of landslide types identified by most classifications also provides an approximation of the range of potential impacts. Although the impact of a given landslide type is not always predictable, the class of landslide does present an indication of the type of movement and its destructive potential. Within the field of landslide research, many different landslide classifications can be found. The most commonly used landslide classifications are based on material type (e.g. rock, debris, earth), mechanisms of movement (e.g. fall, topple, slide, flow, creep) and degree of disruption of the displaced mass. Landslide classifications are discussed by Hutchinson (1988), Crozier (1989), Cruden and Varnes (1996), and Dikau *et al*. (1996). Landslide types are classified as shown in Table 2.1.

In practice, it is difficult to assign a landslide to a particular class. Commonly, landslides are complex processes, for example with rotational shear planes in the upper part and

Table 2.1 *Landslide classification based on Dikau* et al. *(1996)*

Process	Material		
	Rock	Debris	Earth
Fall	Rockfall	Debris fall	Earthfall
Topple	Rock topple	Debris topple	Earth topple
Rotational slide	Single (slump)	Single	Single
	Multiple	Multiple	Multiple
	Successive	Successive	Successive
Translational slide	Block slide	Block slide	Slab slide
Planar	Rockslide	Debris slide	Mudslide
Lateral spreading	Rock spreading	Debris spread	Earth spreading
Flow	Rockflow (Sackung)	Debris flow	Earthflow
Complex	e.g. Rock avalanche, Bergsturz	e.g. flow slide	e.g. slump – earthflow

Figure 2.3 *Earth slides on the slopes converted to mudflows in the valley during a rainstorm in 1977 in Wairarapa, New Zealand (photo by M.J. Crozier)*

flow structures in the lower reach. It is even more complex when several types of slope material are present in the one landslide. Also, external factors determine landslide types. While a given slope segment might fail as a translational debris slide under moderate moisture conditions, the same slide might convert to a debris avalanche or debris flow under wet conditions, thus increasing runout (Figure 2.3). Similarly, an earthslide may change to a mudflow as a result of slope morphological and hydrological conditions. In addition, vegetation cover can also influence the type of movement.

2.4 Impact

The juxtaposition of landslides and human presence exacts a cost. That cost can arise from the damage resulting from landslide impact or from the expense required to sustain measures to mitigate the impact. In a sense there is no escaping the cost; it can be transferred and transformed but, nevertheless, one way or another there still remains a price for living within a hazardous environment.

If landslide hazard is defined as the probability of occurrence of a potentially damaging landslide, the following questions become fundamental:

- What constitutes a damaging landslide?
- Which attributes of the landslide are capable of producing what kind of damage?
- What is the recurrence frequency for landslides either on specific sites, or somewhere in the region?

The following sections set out to address these questions.

Landslide impact is discussed in terms of the physical impact *mechanism* exhibited by the landslide (the destructive behaviour of material as it moves downslope) and the *type* of impact. The type of impact refers to how these slope movements can create damage in time and space. Landslide impacts can be direct or indirect, immediate or delayed, and in some instances generate consequential hazards. Not all landslides are equally hazardous.

2.4.1 Impact Mechanisms

Landslides directly affect physical elements at risk by a range of impact mechanisms, including: burial, collision impact, earth pressures, differential shearing in tension, compression or torque, plastic deformation (flow), by object displacement and by removal or deformation of valued ground, such as productive soil and foundation substrate. The degree to which these mechanisms are manifest is generally reflected by the type of landslide. However, many landslides exhibit complex behaviour and a variety of impact mechanisms may be represented in the one landslide type. For example, an earth slide may change to a mudflow as a result of slope morphological and hydrological conditions. This increases difficulties of assigning structural damage to specific landslide types. Despite this problem, a classification scheme has been suggested by Flageolett (1999) in Figure 2.4.

2.4.2 Physical Impact Type

The elements subject to these impact mechanisms show several types of physical impact. The impacts may be direct or indirect, acute (immediate) or chronic (delayed), or may lead to the development of consequential hazards. *Direct impacts* are those consequences incurred by direct physical contact with the landslide itself. *Indirect impacts*, on the other hand, are changes brought about in the properties and behaviour of other natural systems as a result of landslide activity. Some of these induced changes may give rise to consequential hazards, for example a wave generated by a landslide entering a reservoir. Indirect impacts can be immediate or delayed, occur in the proximity of the landslide or at some distance from the landslide site. *Acute impacts* are short-lived, while *chronic impacts* may be manifest over a longer period of time.

2.4.3 Direct Impacts

Direct impacts arising from landslide activity upslope of a site can affect structures by: collapse or damage by crushing from burial, collision impact, associated air blast, or distortion by gradual earth pressure (Casale and Margottini, 1999). The impact on humans and animals from these mechanisms may include loss of life or injury by trauma from collision impact, crushing or asphyxiation, whether directly affected by the landslide or indirectly through structural collapse. Vegetation, including large trees, may be root-wrenched, uprooted or buried. Landslide deposits can also extensively inundate productive agricultural land, at least temporarily reducing productivity (Figure 2.5).

Landslides occurring underneath or downslope of structures cause removal of basal support, leading to collapse, deformation and displacement (Figure 2.6). If a structure intersects a shear or tensional rupture zone, damage can result in simple relative displacement (e.g. rupture of a pipeline) or distortion and collapse (Figure 2.7). Where landslide

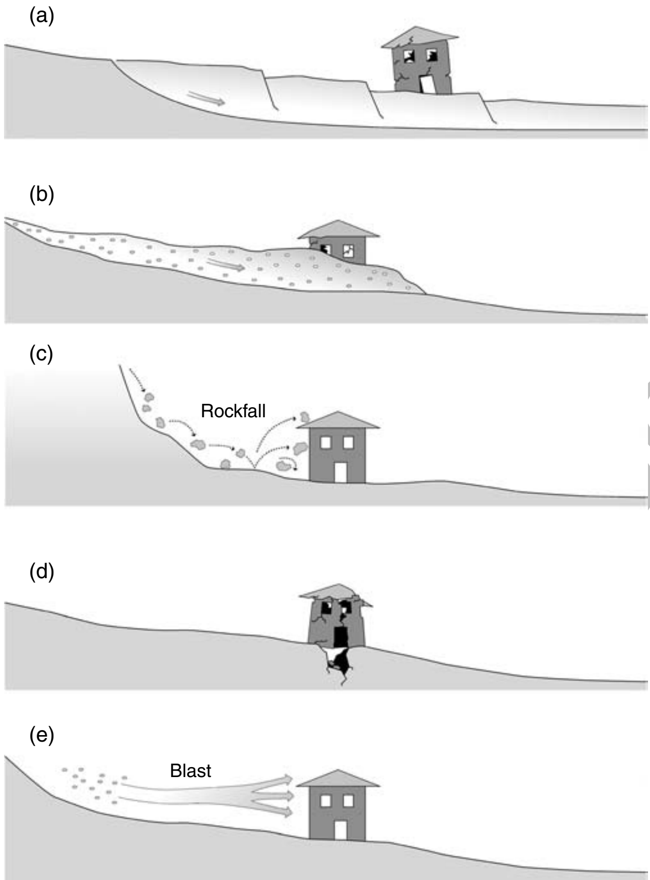

Figure 2.4 *Schematic representation of structural damage to buildings for different landslide types (according to Flageolett, 1999). (a) Damage is assigned to slide and flow processes, (b) to flows, (c) to falls and topples, (d) to subsidence and (e) to rock avalanches or large rock failures, such as a Bergsturz*

displacement occurs by relatively undeformed blocks, the physical impact to structures may result in their translocation rather than destruction. A schematic diagram of a compound landslide showing typical destructive components such as crown scarp, tensional zones, lateral shears and compressive zones is shown in Figure 2.8. Acute impacts that occur instantaneously or take place over a short period of time are usually much more life-threatening than chronic impacts, which nevertheless can create expensive ongoing problems (Figure 2.9).

2.4.4 Indirect Impact

Indirect impacts may involve the interaction of landslides with other systems or processes, for example fluvial systems, artificial or natural lakes, and they may be responsible for

Figure 2.5 *Removal of soil from the slope and burial of soil on valley floor in the rainstorm of 6 August 2002, Gisborne, New Zealand (photo by M.J. Crozier)*

tsunami, coastal erosion, soil depletion and increased storm runoff. These impacts are described in more detail below.

Many of the most serious indirect impacts arise from the coupling of landslides with the fluvial system. The way in which landslides interact with the fluvial system can have important implications for the resultant level of hazard. Korup (2003), in his study of the unpopulated southwest Southern Alps of New Zealand, attributes potential impact to the orientation of the landslide track with respect to the fluvial receiving system (Table 2.2). The range of on-site impacts resulting from landslide/fluvial coupling is given in Table 2.3.

There is a range of long-term, long-range effects associated with the coupling modes and direct impacts described in Tables 2.2 and 2.3, which include consequential hazards such as channel avulsions at the landslide site, or upstream and downstream of the landslide body as well as aggradation and subsequent potential for landslide dam-burst events. Costa and Schuster (1988) observe that 85% of landslide dams fail within one year of emplacement. Dam failures may take place as catastrophic events causing widespread damage and destruction downstream (Korup, 2002). Some landslide dams, however, may last for thousands of years and affect the fluvial system by entrapment of bedload and downstream starvation of sediment (Figures 2.10, 2.11 and 2.12) (Riley and Read, 1992).

Figure 2.6 *House destruction in the graben of Abbotsford landslide, 8 August 1979, Dunedin, New Zealand (photo by Allied Press Ltd)*

Figure 2.7a *Left lateral shear surface of mudslide, Otago Peninsula, South Island, New Zealand (photo by M.J. Crozier)*

Figure 2.7b *Right lateral shear zone of mudslide, Biferno River Valley, South Italy (photo by M.C. Salvatore)*

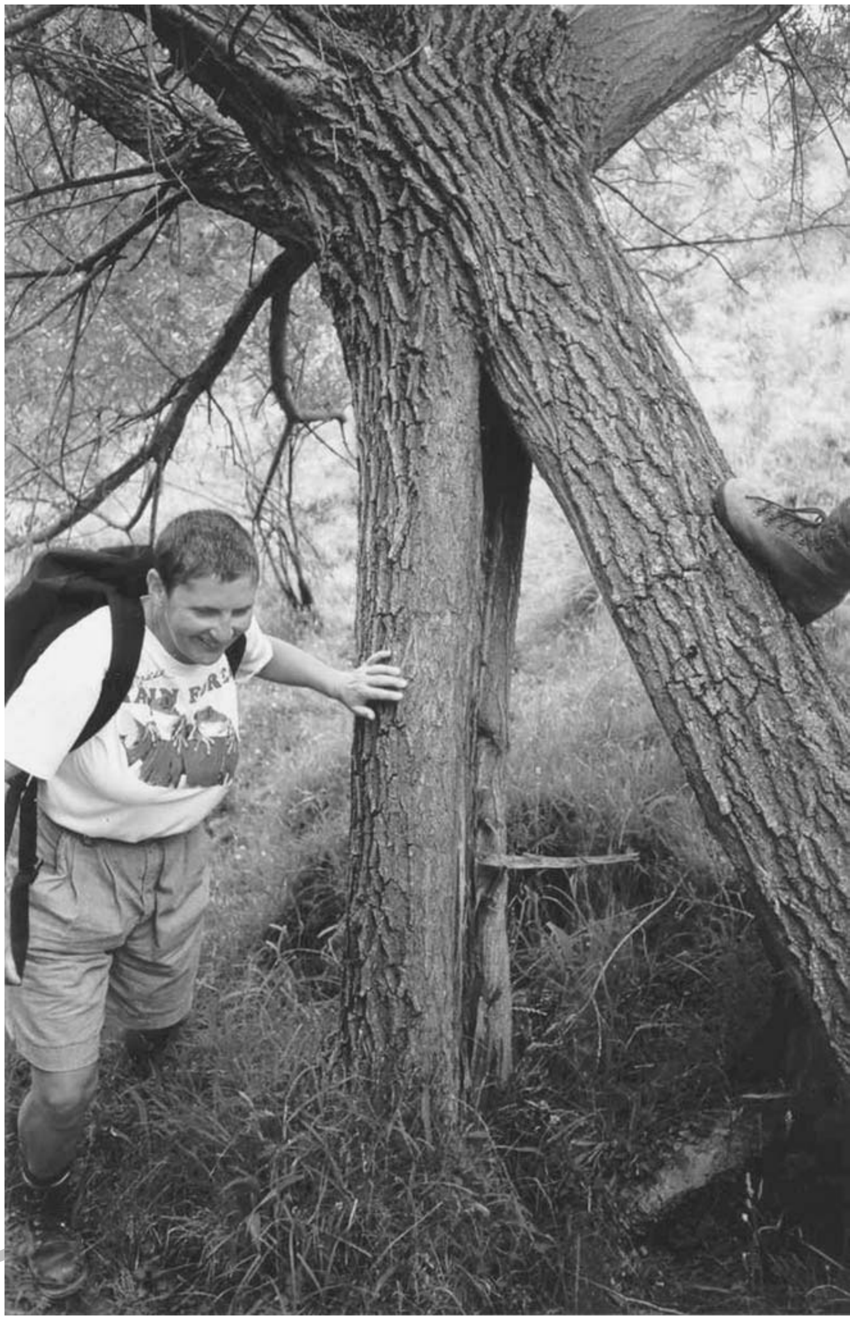

Figure 2.7c *Tree split by left lateral shear zone, Gisborne, New Zealand (photo by M.J. Crozier)*

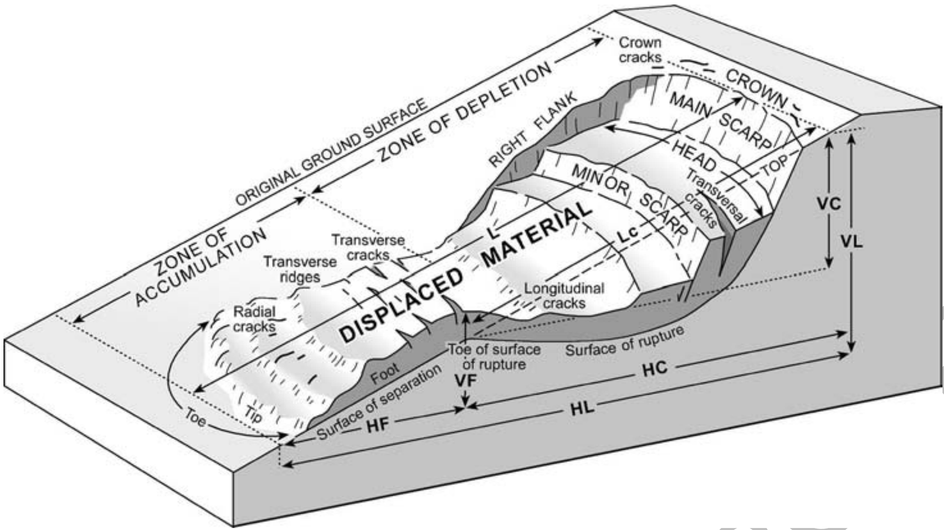

Figure 2.8 *A compound landslide showing typical destructive components such as crown scarp, tensional zones, lateral shears, compressive zones. Note: H is the horizontal distance and V is the vertical distance for various parts of the landslide indicated (based on Varnes, 1978)*

Figure 2.9 *Instantaneous failure, resulting from rainstorm of December 1976, Central Terrace Wellington, New Zealand (photo by M.J. Crozier)*

Table 2.2 *The coupling mode: the geometric relationship between landslides and the fluvial system (The ALPIN classification), after Korup (2003)*

Geomorphic coupling interface class	Subclass	Diagnostic characteristics
(A) Area		Very large landslide bodies in excess of 100 km^2 that obliterate low-order drainage divides and reorientate drainage systems
(L) Linear		More than 50% of the runout direction of landslides is oriented in the direction of the fluvial drainage system
(P) Point		Emplacement of the landslide deposit is normal or near normal to the planform direction of the channel. This mode of coupling favours the development of landslide dams
(I) Impounded		Landslides terminate in a standing water body, e.g. fjords, moraine/landslide or floodplain lakes
(N) Nil		Landslide are in a state of geomorphic decoupling, with no physical contact between the toe of the deposit and the channel system
	Nh	Landslide deposits are stored in morphological or structural depressions (colluvial storage)
	Nv	Landslide deposits are stored on valley fill, e.g. floodplain alluvium, terraces, fans, moraines or older landslide deposits
	Ni	Landslides buffered on ice or snow

Table 2.3 *On-site impact on fluvial systems resulting from the coupling mode, after Korup (2003)*

Geomorphic impact class	Diagnostic landform
Buffered	Landslide makes no physical, direct contact with the fluvial system
Riparian	Direct contact with the channel, where fluvial erosion dominates, controlling landslide initiation and removal
Occlusion	Landslide diverts river channel around toe of landslide, with up- and downstream influence
Blockage	Occurrence of a landslide dammed lake
Obliteration	Complete burial of extensive valley-floor section with drainage reversals, landslide ponds and dams

Impounded coupling (Table 2.2) may produce some of the most intractable problems for hazard estimation. Landslides on the margins of reservoirs, depending on the velocity of emplacement and volume of material involved, have the potential to create large waves that can overtop or destroy dams and create serious catastrophic inundation downstream. A tragic example of this type of consequential hazard emptied the artificial lake in Vaiont in 1963, causing the deaths of over 2500 people in the Italian town of Longarone and surrounding villages (Petley, 1996; Voight and Faust, 1992). A description of the

Figure 2.10 *Occlusion impact, Shotover River, Otago, New Zealand (photo by Allied Press Ltd)*

administrative response to the Vaiont disaster is given in Chapter 9 by Hollenstein. Similar catastrophes have occurred in Peru, when snow and rock avalanches have entered moraine-dammed lakes, causing overtopping or dam breach. The major objective for hazard estimation in these cases is the determination of likely landslide volumes and velocities (Gillon and Hancox, 1992). If first-time failures are being assessed, the initial problem is the estimation of landslide volume. In the case where existing landslides occur on reservoir margins, it may be possible to estimate volume by locating boundary shear surfaces, but the question of velocity is much less readily resolved. It is generally assumed that in an existing landslide, brittle failure, often associated with rapid movement, will have already taken place and that subsequent movement will mobilize residual strength and result in more gradual displacement. However, instances have been recorded where the reactivation of existing landslides has resulted in high-velocity surges of movement (Prior and Stephens, 1972).

Subaerial coastal landslides and submarine landslides, in some cases of huge dimensions, are capable of generating high-magnitude tsunami (Dawson, 1999; Driscoll *et al*., 2000; Hampton *et al*., 1996). For example, different ages of Holocene mass movements are known from Norway fjords (Boe *et al*., 2003). One of the best known is the Storegga submarine landslide, which occurred between 7300 and 6400 C^{14} yr BP

Figure 2.11 Blockage impact: lakes formed by earthquake-triggered landslides circa 1300 years BP, Waverley, New Zealand (photo by Lands and Survey, New Zealand)

(Grauert *et al.*, 2001) and from the resulting tsunami caused considerable impact along the Norwegian coast (Bondevik *et al.*, 1997), and also in the Faeroe Islands (Grauert *et al.*, 2001) and Scotland (Dawson and Smith, 2000). Similarly, the Sissano Papua New Guinea tsunami disaster of 1998 is thought to have been caused by a seismically triggered submarine landslide (Tappin *et al.*, 2001).

More subtle, but none the less important, are the impacts of landslides which remove or destroy the pedological soil, particularly in areas relying on primary production from those soils. A number of studies in New Zealand (e.g. Crozier *et al.*, 1980; Page *et al.*, 1994) have shown that, in one event, multiple landslides can remove soil from up to 10% of areas involving hundreds of square kilometres (Figure 2.13). The cumulative effect of a series of these events in New Zealand hill country (40% of NZ land area) has seen soil depleted from 20–50% of the area in the hundred or so years since forest clearance. Each landslide usually removes the entire soil mantle from the underlying bedrock. Although these sites regain a soil cover with time, 20-year-old landslides have been shown to yield only 70–80% of the productivity on undisturbed slopes and even after 80 years productivity is still only 80% (Lambert *et al.*, 1984). The limiting factor to growth appears to be not so much nutrient availability as soil moisture availability in the thin recovering soil.

A further indirect impact, resulting from the removal of soil by shallow landslides and the consequent reduction of slope water storage capacity, is increased storm runoff (e.g. Dietrich *et al.*, 1993). This effect, combined with the reduction in channel capacity from landslide-derived sediment, increases the frequency and magnitude of overbank flooding (Figure 2.14).

Figure 2.12 *Linear coupling: deposits from the Vancouver Ridge landslide totalled 170 million tonnes and travelled 3.5 km downstream, August 1989, Ok Tedi, Papua New Guinea (photo by M.J. Crozier)*

Figure 2.13 Shallow earthflows, Kiwi Valley, Wairoa, New Zealand, triggered by a rainstorm of 965 mm in 72 hours in 1977 (photo by Hawke's Bay Catchment Board)

Slow-moving deep-seated mudslides and earthflows may have the opposite effect on slope hydrology compared to the impact of rapid shallow soil failures. The progressive surface deformation within and upslope of the displaced mass tends to disrupt and obliterate existing drainage lines and channels and impound water on the slope (Figure 2.15). This gives rise to surface ponding and saturated hollows, leading to a die-off of the usual slope vegetation and the ultimate replacement with more water-tolerant species.

2.4.5 Impact Characteristics (Intensity) of Landslides

The mechanism and severity of impact depends on the type of landslide, its impact characteristics, and the location of elements at risk with respect to the particular morphological components of the landslide. In their review of 23 case histories of catastrophic landslides in South America, Schuster *et al*. (2002) observed that most casualties were caused by high-velocity debris avalanches and high- to medium-velocity, highly mobile, long-runout debris flows. The impact potential or power of a landslide is primarily a function of its mass and velocity. At the most dangerous end of the power spectrum are rock avalanches that can attain volumes of tens of millions of cubic metres and travel at velocities up to 60–80 m/s (McSaveney, 2002).

Figure 2.14 *Channel instability induced by reduction of storage capacity on slopes by regolith landslides, January 1990, Waitotora, New Zealand (photo by M.J. Crozier)*

The range of landslide velocities is shown in Table 2.4. Although a given landslide type may carry out most of its movement at a characteristic velocity, it may be also be capable of moving at a wide range of velocities. For example, a rock slide can creep at a rate of cm/year, but most of its displacement will be at rates of cm/s to m/s.

The appropriate management response to a landslide hazard depends on the expected velocity of movement. For example, a large rotational landslide creeping at rates of mm/year can still be used for settlements or infrastructure lines. Appropriate counter-measures such as flexible sewage lines, moveable basements for railway tracks, or strong house foundations might allow intensive usage (refer to Chapter 19 for such geotechnical applications). The decision on whether a usage is still economically viable is mostly based on cost/benefit analysis. In contrast, if the similar block moves with a speed of cm/day, safe, economic use of the site may not be possible. Figure 2.16 gives schematic examples of the role of velocity of movement to the consequences.

In general, major factors controlling the speed of movement are the mass in motion, the horizontal and vertical travel distances and thus the slope angle, the moisture of the transported material and, for lower-magnitude events, the vegetation cover. These factors also influence the runout distances (Hungr, 1995). Physical models are regularly used to calculate runout distances for different landslide types (e.g. Miao *et al.*, 2001). If the landslide size/magnitude increases, movement patterns become too complex to be accurately modelled (Hutter *et al.*, 1996). Another approach involves empirical models, relating for example landslide dimensions or/and topographic conditions to volume in order to

Figure 2.15 Landslide dam four days after initiation, August 2002, Gisborne, New Zealand (photo by M.J. Crozier)

approximate runout length (Rickenmann, 1999). Various authors have applied these models to assess potential runout zones (e.g. Corominas, 1996; Crozier, 1996; Fannin and Wise, 2001; McClung, 2001). If linked to frequency of landslides events, either established by historical information or by investigating the recurrence intervals of the trigger, the runout zones can be transferred to hazard zones (Glade, 2002). Extreme runout zones of some kilometres have been observed for the Parinacota debris avalanche, northern Chile by Clavero *et al*. (2002) and for Mt Cook, New Zealand by McSaveney (2002).

With slow-moving landslides, impact potential is also related to the amount of displacement per unit of time providing destructive earth pressure and differential shearing rather than collision impact. Next to volume and velocity, the degree of disruption of the displaced mass influences the type of impact and the degree of destruction of elements at risk. The depth of movement is also an important impact characteristic and dictates not only the type of impact but also the type of remedial measures than can be successfully applied.

2.5 Frequency–Magnitude Issues

As already indicated, the frequency and magnitude of landslides are of particular concern for any hazard and risk analysis. There are two approaches to assessing frequency and magnitude: first, temporal investigations that may include stability analysis of a site

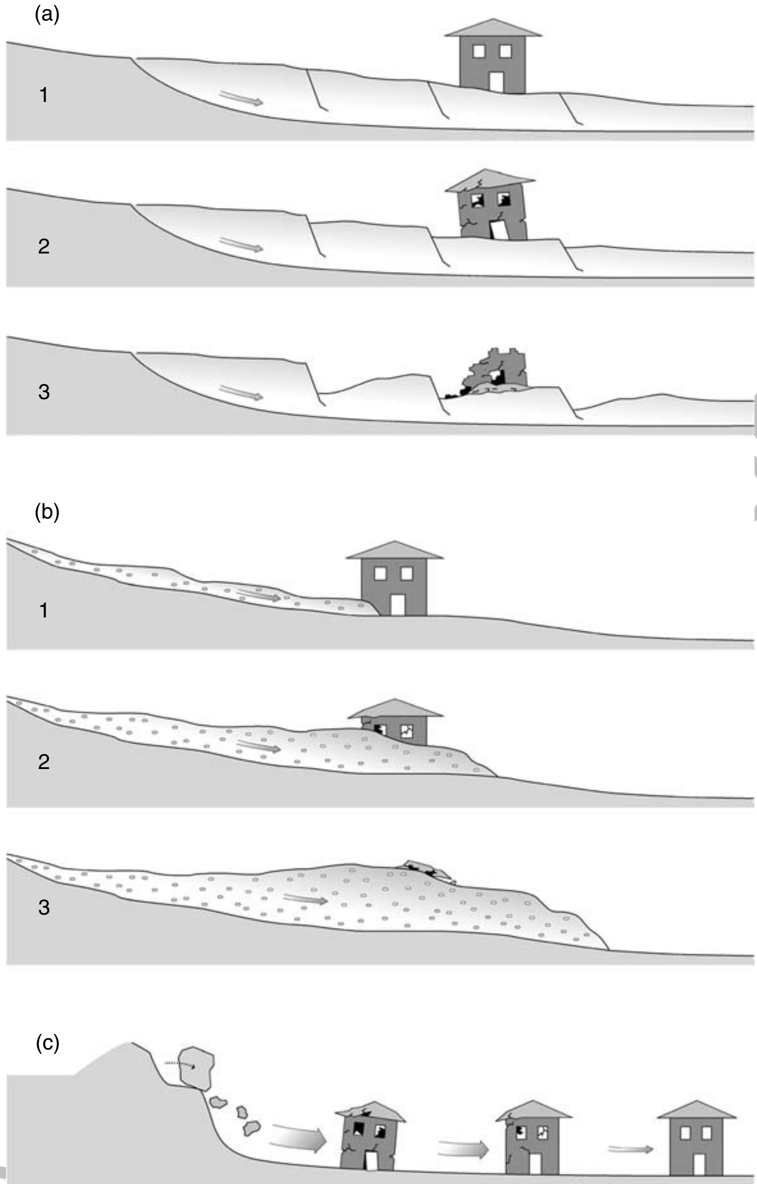

Figure 2.16 *Schematic consequences of different velocities of movement for different landslide types (adopted from Flageolett, 1999). (a1) A slide creeps or (a3) fails suddenly. (b1) A debris flow progresses in low or (b3) high velocities with respective changes in flow height. (c) A slow- or fast-moving rockfall damages, depending on the size and consequent momentum, elements at risk to a different degree. The degree depends on the distance between the process and the location of the element at risk*

Table 2.4 *Classification of velocity of movement according to Cruden and Varnes (1996) and Australian Geomechanics Society (2002)*

Speed class	Description	Velocity (mm/s)	Typ. velocity	Probable destructive significance
7	Extremely fast			Disaster of major violence, buildings destroyed by impact of displaced material, many deaths, escape unlikely
		5×10^{3}	5 m/s	
6	Very fast			Some lives lost; velocity too great to permit all persons to escape
		5×10^{1}	3 m/min	
5	Fast			Escape evacuation possible; structures, possessions and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very slow			Some permanent structures undamaged by movement
		5×10^{-7}	16 mm/year	
1	Extremely slow			Imperceptible without instruments, construction possible with precautions

or analysis of external triggers or landslide occurrence (e.g. Glade, 1998; Hungr *et al.*, 1999), and second, the spatial analysis of frequency distributions of landslide size in a given area (e.g. Guzzetti *et al.*, 2002; Hovius *et al.*, 1997).

Temporal studies can either investigate the response of a single landslide to climatic inputs or relate the occurrence of landslides within a larger region to climatic conditions that characterize the region; in this case occurrence within a region, rather than the specific landslide location, is the parameter of interest. The simplest approach is to characterize the behaviour of the triggering agent at the time of landslide occurrence. For example, this may result in the establishment of a threshold rainstorm value, above which landslides can be expected to occur (Glade, 1998). A more advanced technique is to associate other temporal information with the triggering threshold. For example, the antecedent climate or slope hydrological conditions may also be taken into account (Glade *et al*., 2000). By including information on physical characteristics of the soil, these models can be refined for specific environmental conditions (Glade, 2000). The established thresholds can then be used to calculate the probability of exceedence of this climatic threshold within different periods of time. Such an analysis has been undertaken by Crozier and Glade (1999) and one result is shown in Figure 2.17. By adding the threshold lines, respective values can be used for estimation of the frequency of a landslide-triggering rainstorm event for different time periods.

The determination of the frequency of occurrence based on triggering thresholds has so far been developed for regional scale analysis based on the history of landslide occurrence. Although the models have the capacity to be run for different landslide types, this has not been performed yet due to data limitations.

In addition to temporal analysis, spatial impacts of widespread landsliding following an intense triggering event have also been investigated in a number of localities. The sort of event that is suited to this type of analysis is shown in Figure 2.18. Spatial analysis uses frequency–area statistics of landslides. Results of analysis by different authors show that these distributions follow commonly a power-law relation with a negative exponent (e.g. Czirok *et al*., 1997; Guzzetti *et al*., 2002; Hovius *et al*., 1997). Essentially these show that small landslides are common while large landslides are relatively rare. This relationship appears to remain constant irrespective of the size of the data set, over a population range from 100 to more than 10 000 landslides. Also, the power–law distributions seem to be

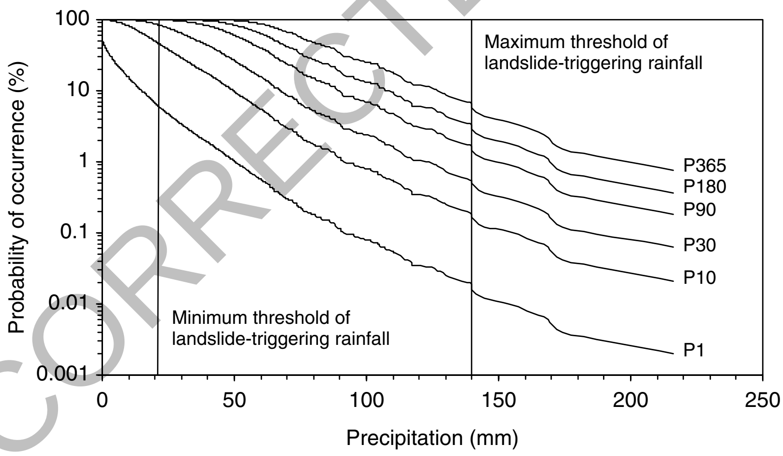

Figure 2.17 *Probability of occurrence of daily precipitation equalling or exceeding given values in Wellington, New Zealand. (Note: different lines refer to a probability of occurrence of a specific rainfall magnitude at each single day (P1), within a period of 10 days (P10), within a month (P30), etc. The empirically established minimum and maximum thresholds of landslide-triggering rainfall (140 mm) are shown by the thin vertical lines. Method is described by Crozier and Glade, 1999.)*

Figure 2.18 *Widespread landsliding as a result of Cyclone Bola in March 1988, East Coast, North Island, New Zealand (photo by N. Trustrum)*

independent on the type of trigger. For example, Guzzetti *et al*. (2002) found a comparable distribution for both earthquake- and snowmelt-triggered landslides (Figure 2.19). This is a particularly interesting result with the potential to be used in hazard and risk assessments in the future.

Whether spatial or temporal approaches are used, they both require a reliable database. It is clear that further use of these methods depends on a standardized system for collecting and archiving data on landslide occurrence. For temporal studies, particularly those requiring correlation with climatic conditions, it is essential to have accurate information on the date of occurrence. An approximation of period of occurrence may be obtained through the comparison of time-slice air photography. In some cases, however, no information on either the trigger or the time of landslide occurrence is available. In such cases, temporal information can only be given in relative terms. A reference of features indicating activity or relative age of landslides was proposed by Crozier (1984). Relative age assessments can be used to determine whether landslides belong to the same age cohort and therefore indicate triggering by a single event (Table 2.5).

More robust age information for longer time periods, for example the Holocene, can be obtained using absolute dating techniques (e.g. Lang *et al*., 1999). The material dated is generally either sediment, in particular quartz grains (TL, OSL), or buried organic material (C^{14}). Both materials can be taken from the basins or ponds that have developed within the previously moved mass, from sediments in dammed lakes, or from fossil surfaces buried by the landslide. A number of studies on the temporal occurrence of landslides in the Holocene with worldwide examples is given by Matthews *et al*. (1997).

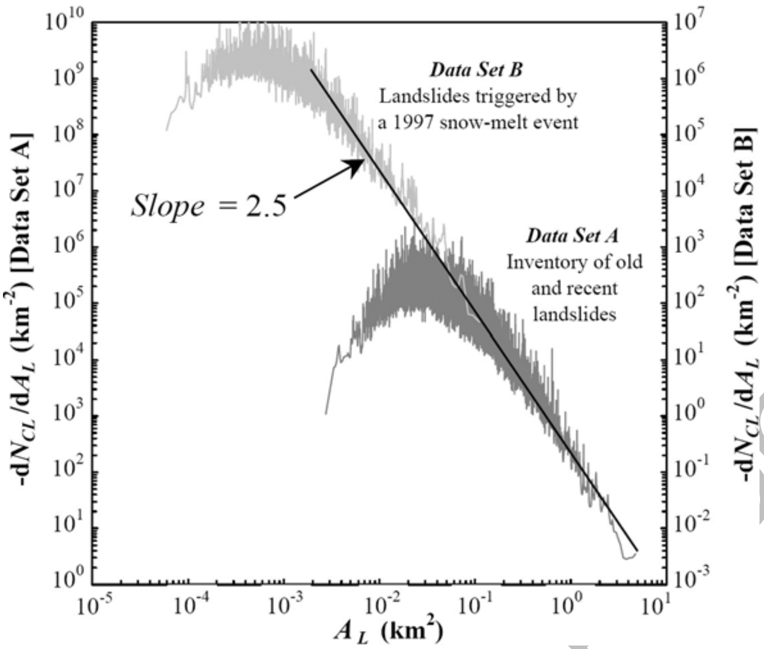

Figure 2.19 *Non-cumulative frequency-area distribution of central Italian landslides (Guzzetti* et al.*, 2002). (Note:* A_L *= landslide area; d = derivative;* N_{CL} *= cumulative number of landslides with areas greater than* A_L*.)*

Databases on landslides may have a wide range of accuracy. As one might expect, the more recent the landslides, the greater the level of available detail. Also, in assessing older events, evidence of some of the smaller landslides may have become obliterated. Therefore, in any frequency–magnitude investigation, it is most important to consider the limitations of the database, particularly with respect to the age of the landslides examined.

Although general frequency–magnitude assessments are at the core of landslide hazard estimation, magnitude itself (as measured by volume or area) may not be the most important parameter in producing impact. In many cases, other impact characteristics such as velocity and degree of disruption or runout distance may be more important. There have yet to be any comprehensive assessments of the frequency of occurrence of some of these higher-impact parameters.

2.6 Vulnerability with Respect to Landslide Types

Various approaches can be used to assess vulnerability to different landslide types (reviewed by Glade, 2004). These approaches vary significantly in the detail of analysis and the final vulnerability values. In contrast to Heinimann (1999b), most approaches do not distinguish between landslide types (e.g. Leone *et al.*, 1996; Ragozin and Tikhvinsky, 2000; Wong *et al.*, 1997) or landslide magnitudes (e.g. Leone *et al.*, 1996; Michael-Leiba *et al.*, 2000; Ragozin and Tikhvinsky, 2000; Wong *et al.*, 1997). Also vulnerability estimates for elements at risk vary. Although the vulnerability of buildings is assessed

Table 2.5 *Features indicating activity or relative age of landslides (after Crozier, 1984)*

Active/Recent	Inactive/old
Scarps, blocks and crevices with sharp edges (Fig. 2.20a)	Scarps, blocks and crevices with rounded edges (Fig. 2.20b)
Crevice and depressions without secondary depositional infilling	Crevice and depressions with secondary depositional infilling
Secondary mass movement on scarp	No secondary mass movement on scarp
Surface-of-rupture and marginal shear surfaces show fresh slikensides and striations	Surface-of-rupture and marginal shear surfaces show no or subdued slikensides and striations
Fresh fractured surfaces on blocks, little lichen cover	Weathering on fractured surfaces of blocks, established lichen cover
Disarranged or non-integrated drainage system; many ponds and undrained depressions	Integrated drainage system
Pressure ridges in contact with slide margin	Deflated lobes and abandoned levees
No soil development or airfall deposits on exposed failure surfaces	Soil development on exposed failure surfaces, mantle of airfall deposits
Presence of fast-growing, colonizing vegetation species on disrupted surfaces	Presence of slow-growing, climax vegetation species on disrupted surfaces
Distinct vegetation differences 'on' and 'off' slide	No distinction between vegetation 'on' and 'off' slide
Tilted trees with no new vertical growth	Tilted trees with subsequent vertical growth
No new supportive, secondary tissue on trunks	New supportive, secondary tissue on trunks

in terms of degree of loss (e.g. Leone *et al.*, 1996), absolute values of vulnerability differ significantly. Similarly, vulnerability of people is treated in a variety of ways. Some authors distinguish between different levels of injury and the 'final' loss of life (e.g. Ragozin and Tikhvinsky, 2000), while others just define the probability of loss of life (e.g. Michael-Leiba *et al.*, 2000; Wong *et al.*, 1997). In addition, the resultant absolute values for vulnerability are spread over a wide range and make consequent comparisons of approaches very difficult (Glade, 2004).

Various reasons might explain these large differences:

- Not all authors explicitly state in detail how the values of vulnerability for different landslide types were derived. No uniform methodology exists. It is suspected that most of the values have been assumed.
- Most studies are based on empirical data, for example Wong *et al.* (1997) used such an approach for Hong Kong.
- Local historical databases have been reviewed; for example Michael-Leiba *et al.* (1999) assessed the vulnerability of buildings and people by using the Australian Landslide Database and of roads by information provided by the Cairns City Council.

Figure 2.20 *(a) Landslide displaying features of relative youth – disrupted blocks with sharp distinctive form, dated at circa 1.3 thousand years BP. (b) Landslide displaying features of greater age – subdued, smooth surface with soil mantle of airfall deposits, dated at circa 31 thousand years BP*

Table 2.6 *Vulnerability of a person being affected by a landslide in open space, in a vehicle and in a building (modified by Glade, 2004 after Wong* et al.*, 1997)*

Location	Description	Vulnerability of a person		
		Data range	Recommended value	Comment
Open space	Struck by rockfall	0.1–0.7	0.5	May be injured but death unlikely
	Buried by debris	0.8–1	1	Death by asphyxia
	Not buried, but hit by debris	0.1–0.5	0.1	High chance of survival
Vehicle	Vehicle is buried/crushed	0.9–1	1	Death almost certain
	Vehicle is damaged only	0–0.3	0.3	High chance of survival
Building	Building collapse	0.9–1	1	Death almost certain
	Building inundated with debris and person is buried	0.8–1	1	Death highly likely
	Building inundated with debris, but person is not buried	0–0.5	0.2	High chance of survival
	Debris strikes the building only	0–0.1	0.05	Virtually no danger

Derived results are thus heavily dependent on such databases containing socio-economic indicators of community vulnerability to natural hazards (e.g. King, 2001).

- Back analysis of specific past events; for example Ragozin and Tikhvinsky (2000) examined past landslide and earthquake events and Heinimann (1999a, 1999b) investigated past events and derived estimates, but assumed missing values.

Indeed, uncertainty is inherent in all different vulnerability studies, but the margin of error remains unknown in detail. It can be concluded that – although Heinimann (1999a, 1999b) introduces a very detailed approach in determining risk to gravitational mass movements – a general strategy in determining vulnerability of elements at risk to specific landslide types and magnitudes is missing. This is a major drawback for any landslide risk analysis. Most values adopted in landslide risk analysis are based on experience of previous events and on common sense. One example of such a classification for different landslides and associated vulnerability of a person in different situations is given by Wong *et al*. (1997) (Table 2.6).

2.7 Conclusion

Landslides are natural events occurring worldwide and pose a threat to affected communities. Conditions promoting slope instability include predisposing factors, preparatory factors, triggering factors and sustaining factors. The importance of each factor varies from place to place and differs for each landslide type. Some of these causative factors are readily affected by human activity, some are controllable for mitigation purposes while others we must simply learn to live with.

The physical impact potential of landslides is a function of the mass of displaced material, depth, degree of disruption, and velocity. It is clear that no uniform impact condition can be unequivocally related to a specific landslide type. In response to external and internal factors, similar landslide types can behave differently; thus a careful assessment of movement patterns is essential. Landslide impacts are described in terms of their impact mechanisms, the physical impact type, and the immediacy of their effect over time and space. Frequency–magnitude issues of landsliding are discussed for both temporal and spatial analysis. Finally, the difficulty of establishing vulnerability to the landslide threat is discussed. The following conclusions on the nature of landslide hazard impact can be derived:

- No unique and simple method is currently available for the prediction of impact within landslide risk analysis.
- Impact estimates are heavily dependent on historical data for the region and the landslide type respectively, and therefore may not have direct relevance to the estimation of future risk.
- Even when information on past events is available, details of landslide impact to elements at risk with respect to specific type and magnitude of process are frequently missing.
- If none of the information sources is available, impacts to elements at risk have to be estimated based on examples from other regions, or even other processes (e.g. earthquakes, floods).

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