Chapter 2

Landslide Causes and Triggers

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ABSTRACT

The stability of a slope is influenced by a variety of time-independent and time-dependent factors, which, when unfavorably aligned, can lead to landsliding. Assessing landslide causes is useful for hazard analysis, mitigation of slope instability, and for considering the role of landslides in landscape systems and evolution. Geological and geomorphological conditions (e.g., material type, strength and structure, and slope angle) predispose slopes to failure; knowledge of these conditions can help to predict the location, types, and volumes of potential failures. Determining when a slope will fail is a considerably more difficult challenge, largely due to the difficulty of observing or predicting the processes of material strength degradation. This chapter describes concepts of stability and explores some of the major causes and triggers of slope failure and opportunities for further research.

2.1 INTRODUCTION

On the 8th of August 1979 in Abbotsford, New Zealand, several weeks of preliminary movements culminated in the rapid failure of an approximately 5 million m^3 block slide in a residential area. The cost of the Abbotsford Landslide amounted to some NZ$10−13 million and included the loss of 69 houses, but no human lives (Hancox, 2008). When landslides or other hazards result in financial or human losses, a question of blame will often arise, particularly in cases where insurance companies need to make loss adjustments. This, and the desire to prevent similar disasters in the future, necessitates investigation into the causes of a landslide. Furthermore, to gain an appreciation of the role of landslides in landscape systems and in the geomorphic evolution of landscapes, it is necessary to have some knowledge of the factors that determine where and over what timescales landslides are likely to occur or have occurred. As with almost every other landslide, the cause of the Abbotsford Landslide cannot be put down to a single factor; its

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failure was the result of the convergence of a series of unfavorable stability conditions, both natural and human induced. Hancox (2008) reports on the results of a Government Commission of Inquiry which set out to identify the causes of this landslide. The following factors were considered to be of importance:

1. Unfavorable geology, consisting of weak clay layers in gently tilted strata.
2. Removal of support by quarrying at the toe of the slope 10 years prior to failure.
3. A long-term rise in groundwater resulting from a leaking water main above the slide area and a natural increase in rainfall over the preceding decade.
4. Rainfall during the last few days of movement, which by itself may not have been the difference between failure and stability, but likely influenced the timing and nature of the landslide's final rapid movement.

Several causes of minor importance were also recognized, such as increased loading from urban development and the historical clearance of native vegetation. Despite all of these causes, the disaster, rather than the landslide event, stems from the decision to build (perhaps unknowingly) on terrain susceptible to landsliding without adequate precautionary mitigation measures in place. Although land use decisions were the ultimate cause of the disaster, the purpose of presenting this case study is to highlight that, as with many landslides, none of the recognized factors alone would have been sufficient or necessary to cause the landslide. Assigning responsibility to any person, organization or decision is therefore challenging. Yet, knowledge of the various factors that can cause landslides is invaluable for hazard mitigation. This knowledge helps to identify and avoid human activities that may negatively affect, or be affected by, slope stability, and it improves the capability for predicting natural landslides. For example, providing effective advanced warnings for debris flows requires appropriate triggering thresholds to be set. At which level these thresholds are set, and indeed the identification of the triggers themselves, requires understanding of the various factors causing and triggering debris flows. These factors may include the availability of debris to be mobilized, antecedent soil moisture conditions, rainfall magnitude and intensity, and the condition of vegetative cover. Without sufficient knowledge of contributing instability factors, and the appropriate application of that knowledge, hazard mitigation efforts may be ineffective.

A great deal of scientific observation and enquiry over the past few decades has contributed to more in-depth classification, rationalization, and understanding of the natural and human causes and triggers of landsliding. This has stemmed largely from the disciplines of engineering geology, soil and rock mechanics, and geomorphology. This article does not attempt to list or comment on the history of significant developments in landslide research (which has been done by others; e.g., Crozier, 1986; Petley, 2011), nor does it attempt to describe every known landslide cause. Instead, the work focuses on causes that are of high importance and remain fruitful objectives of scientific research. To begin, slope stability is introduced to provide a conceptual basis for understanding the effects of various slope conditions and destabilizing processes. This is followed by a brief overview of the main types of landslide causes and triggers and our current understanding of these. Finally, a brief synopsis of landslide causes and opportunities for further research is presented.

2.2 CONCEPT OF INSTABILITY

Destabilizing stresses are present within all slopes. Whether or not these stresses (driving stresses) are capable of triggering failure of a given slope at a given moment in time will depend on the relative magnitude of the stresses that resist the tendency for failure; these opposing stresses can be referred to as resisting stresses. Both driving and resisting stresses can change over time. Thus, "stability" is both a relative term and one that refers to a specified time period. The vast majority of existing slopes are stable at this moment in time (otherwise they would be in the process of failing), but every slope has the potential to fail at some future time. The magnitudes of driving and resisting stresses are the result of stability factors, which can be defined as any phenomena that control or influence the forces that determine the stability (Crozier, 1986). Some stability factors are inherent to the slope and unchanging (e.g., lithology), while others may be transient and their influence may vary in magnitude (e.g., porewater pressures).

Stability can be assessed by considering the balance of driving and resisting stresses. The development of shear stresses drives a tendency for failure for most landslide types (with the exception of toppling). The resisting stresses result from reactionary stresses and can be considered as the mobilized shear strength of the slope with respect to the shear stresses. Mobilized strength refers to the strength that resists movement and is distinguished from the "total" strength of the slope, which is arguably an impossible quantity to assess. For example, the movement of an intact slide-prone block (e.g., a rockslide) is influenced by the frictional resistance generated between the sliding surfaces, not the internal strength of the block itself; therefore, only the strength of the failure surface needs to be known to assess the stability of the slide-prone block. However, the assumption that landslides involving sliding are governed by shear stresses alone is an oversimplification. Other (e.g., compressional and tensional) stresses also play a role, especially at the boundaries of the sliding mass and where the landslide mass moves over irregular surfaces.

The balance of resisting and driving forces is often expressed as a ratio, commonly referred to as the factor of safety (FoS):

$$\text{Factor of safety (FoS)} = \frac{\text{resisting stresses (or mobilised shear strength)}}{\text{driving stresses (or shear stresses)}}$$

The FoS equation can be populated with a wide range of parameters which influence the resisting and/or driving stresses. The choice and determination of these parameters depend on the problem being addressed, the physical conditions and processes expected for the slope, and the degree of simplicity or complexity sought. The method of assessing stability by determining the FoS is referred to as limit equilibrium analysis. Examples and explanations of this process and the selection of relevant parameters and variables are provided in numerous texts on slope stability (e.g., Duncan, 1996; Norrish and Wyllie, 1996; Selby, 1993).

The effect of gravity is of fundamental importance in the stability of a slope. The strengths and stresses operating in a slope depend on the way that gravity causes masses within a slope to interact. The weight of material can be resolved into stresses acting normal and parallel to contact surfaces (Figure 2.1). The greater the normal stresses, the greater the frictional strength of the potential failure surface. The relationship between shear strength and the normal stresses is often considered to be linear and governed by the Mohr–Coulomb failure criterion. The greater the stresses acting parallel to the potential failure surfaces, the larger the shear stress. Many of the stability factors discussed below influence the stability of a slope by directly affecting or altering, acutely or chronically, the shear stresses and/or shear strength. Thus, it is useful to keep the relationship between these two stresses in mind.

The term "slope stability" can have different meanings depending on the context of its use or the objectives of its user. It often refers to the inherent

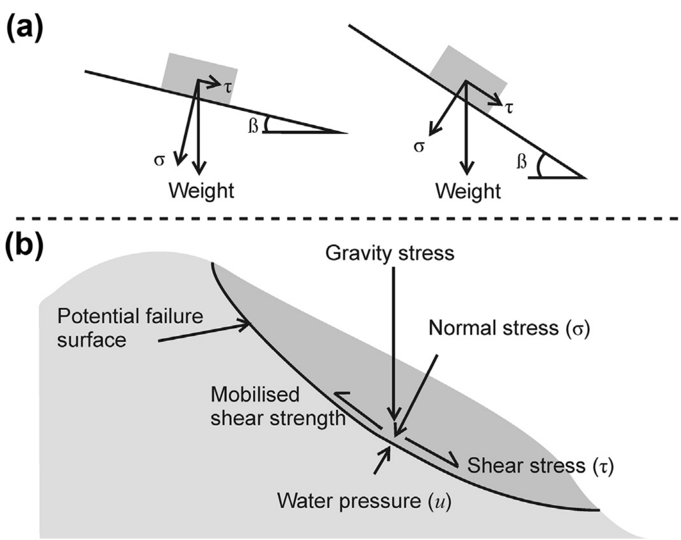

FIGURE 2.1 (a) The influence of slope angle (β) on the relative magnitudes of shear (τ) and normal stress (σ). (b) Stresses acting along a potential failure surface. *Adapted from* Selby (1993), *by permission of Oxford University Press.*

stability or FoS, as determined by the static physical slope properties; for example, all other stability factors being equal, a high embankment is less stable compared with a low embankment. Landslide susceptibility, which is a measure of the inherent stability of a slope or distribution of slopes, treats the term stability in this way, without any consideration of the likelihood of failure. Alternatively, *slope stability* can, more usefully, be a measure of the probability of a failure of an individual slope, which requires consideration of both the stability factors (i.e., slope stability in the previous sense) and the likelihood of a critical failure threshold being exceeded in a given time span[1]. Assessing the stabilities of the two embankments in this sense requires knowledge of the potential failure triggers and their likelihoods during the time period of interest for each embankment. That knowledge must include the probability of the occurrence of a trigger of sufficient (critical) magnitude to induce failure—the critical threshold for failure itself must also be determined probabilistically because it also fluctuates with time over a frequency/magnitude range. The higher embankment is thus not necessarily more likely to fail than the lower embankment because it may exist in an environment less likely to produce a trigger capable of exceeding the critical threshold for stability for that slope.

In considering the causes of mass movements, a distinction must also be made between the terms “failure” and “movement”. Some mass movements only ever exist as a discrete event with the failure resulting in the first and final movement of that material, for example, a rock fall. Other mass movements can exist in a state of transient stability for a long time after failure is first initiated, and be affected by totally different movement triggers or controlling factors to those that initiated the first failure. These slopes may experience discrete periods of instability (movement) and periods of stability (no movement), as is often the case for slopes affected by large, slow-moving rockslides. Other mass movements may evolve from an initially very slowly creeping mass and begin to accelerate as the failure surface develops, culminating in a catastrophic final failure; such mass movements are termed progressive failures (Petley et al., 2005). In such cases, it is not clear to which part of this process the term “failure” applies; the final catastrophic failure only, the initiation of creep, or the entire process (which may take place over an indeterminate amount of time). Perhaps it depends on the scale at which a slope is observed. Petley (2011) explained a distinction between a local and a global FoS for a slope. The global FoS applies to an entire landslide body; although, this in itself may be difficult to define for landslides involving movement of multiple discrete blocks. Failure of the entire mass occurs if the global FoS falls below

1. The parameters used in FoS equations can also be treated probabilistically, in recognition of the difficulty and uncertainty of measuring the absolute value of the parameters (e.g., the friction angle value), with the chosen value, at best, representing a range of possible values that may exist for any one slope (e.g., El-Ramly et al., 2002). Additionally, even the type of failure mechanism may be assessed probabilistically (e.g., Hack et al., 2002).

unity. However, even if the landslide as an entire mass may be stable (global FoS $>$ 1), there may be parts of the landslide body that are locally unstable. Petley pointed out that those unstable parts of the landslide mass will locally undergo deformation, and cumulative deformation of these unstable parts may lead to progressively greater reductions in the global FoS (see Section 2.3.2).

Terms such as "stable", "marginally stable", and "actively unstable" have been introduced in recognition of the need to classify the stability state of landslides as a function of the likelihood of failure (Figure 2.2) (Glade and Crozier, 2005). In this context, "stable" refers to a slope that exists in an environment which is unlikely to produce a trigger sufficient to cause failure or movement of that slope (Figure 2.3). A "marginally stable" slope is one for which a trigger of sufficient magnitude to cause failure can be expected to occur in the prevailing environmental conditions (Figure 2.3). Actively unstable slopes are those that are already unstable and actively moving. A slope may shift between these states with a change in any of a multitude of stability factors. Any factor (or collection of factors) that contribute to the reduction in stability to a marginally stable state can be considered to be a landslide cause (or causes). If any of these factors changes the slope to an actively unstable state, it is considered a trigger. While there can be multiple causes, there is usually only one trigger (Varnes, 1978) (Figure 2.3). Others (e.g., Sowers and Sowers, 1970; Zolotarev, 1973; cited in Varnes, 1978) have previously commented that a landslide trigger is often only the final action that initiates failure of a marginally stable slope, and it may be quite trivial in magnitude (Figure 2.3). This can be likened to the idiom "the straw that broke the camel's back." An astonishing example of movement being triggered by a

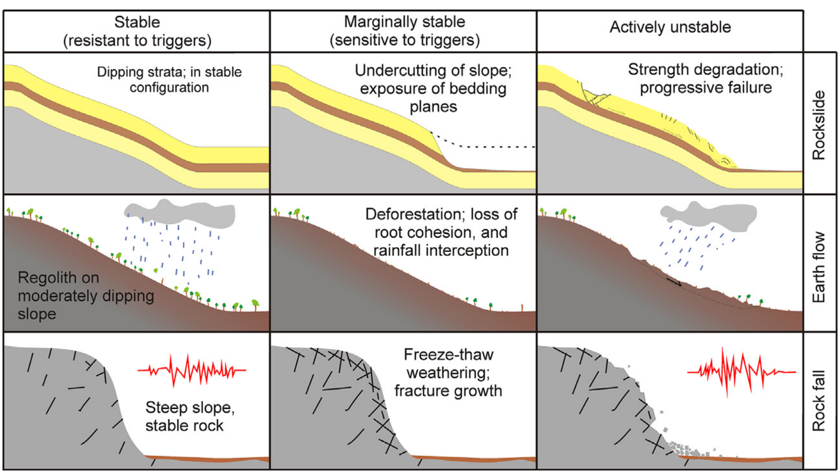

FIGURE 2.2 The relationships between stable, marginally stable, and actively unstable slopes and the interactions of stability factors for a range of landslide types. *Based on Glade and Crozier (2005).*

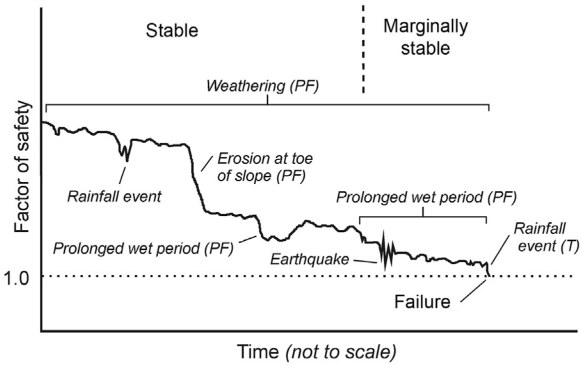

FIGURE 2.3 Schematic representation of the reduction in the FoS of a slope, both through gradual (e.g., weathering) and more discrete (e.g., undercutting) preparatory factors (PF). The resistance of the slope to external processes (potential triggers) lowers through time, eventually bringing the slope to a marginally stable state, whereby it is sensitive to triggering (T) by such events. *Adapted from WG/WLI (1994).*

seemingly trivial force is the Slumgullion Landslide in the United States (Schulz et al., 2009); when the landslide is critically stable due to a combination of other unfavorable stability factors, a tidally-induced state of low atmospheric pressure is sufficient to reduce shear strength and initiate sliding.

The stability factors can be divided into preconditioning, preparatory, and triggering factors (Glade and Crozier, 2005) (Figure 2.2). Preconditioning factors are those that influence the inherent strength of the slope and are generally considered to be temporally unchanging (over human timescales). Factors that reduce the stability over time but do not cause failure or movement are termed preparatory factors, and factors that change a slope to an actively unstable state (i.e., initiate failure or movement) are termed triggers. Descriptions and examples of preconditioning, preparatory, and triggering factors are provided in the following section and examples of each are presented in Table 2.1. Several of these processes can act as either a preparatory factor or a trigger, or both, depending on their degree of activity and the margin of stability of a slope (WG/WLI, 1994). For example, even if an earthquake does not trigger a failure, the shaking may be strong enough to cause deterioration in the strength of material, thus reducing the stability of a slope and potentially allowing a subsequent earthquake of a similar or smaller size to trigger failure. Therefore, earthquake shaking processes can act as both a preparatory factor and a trigger. Some preconditioning and preparatory factors may also be similar. For example, nonzero slope is a precondition for all landslides, but a change in slope angle is considered a preparatory factor. The landslide causes and triggers listed in Table 2.1 include conditions or processes acting both internally and externally to the slope and can reduce the FoS through an increase in the shear stresses, a reduction in the shear strength, or in some cases either of these (Terzaghi, 1950; Varnes, 1978; WG/WLI, 1994).

TABLE 2.1 Examples of Preconditioning, Preparatory, or Triggering Factors and Examples of the Processes Involved

Preconditions
Plastic weak material Sensitive material Collapsible material Weathered material Sheared material Jointed or fissured material Adversely oriented mass discontinuities (including bedding, foliation, cleavage, faults, unconformities, flexural shears, and sedimentary contacts) Contrast in permeability and its effects on groundwater Contrast in stiffness (stiff, dense materials overlaying weak plastic materials)

	Processes		
Preparatory Factors	**Geomorphological**	**Physical**	**Human**
Increase in slope height or steepness	Tilting from tectonism, volcanism, or glacial rebound Fluvial, marine or glacial erosion/undercutting		Slope excavation or slope construction
Debuttressing	Glacier retreat		Unloading of toe of slope
Exposure of potential failure surface	Fluvial, marine or glacial erosion/undercutting		Slope excavation

Reduction in inherent strength	Soil piping or solution weathering	Weathering Stress-induced fatigue	Tunneling, underground mining, deforestation
Loading of the slope	Gradual build up of sediments or vegetation		Construction or emplacement of engineering fill or waste deposits
Long-term increase in groundwater levels		Climate change	Infiltration from storm water or broken pipes Irrigation Removal of vegetation
Triggers	**Geomorphological**	**Physical**	**Human**
Rapid increase in porewater pressures	Undrained loading from rapid emplacement of sediment	Rainfall Thaw of snow/ice	Undrained loading from rapid emplacement of fill or heavy loads
Drawdown of groundwater	Natural dam-breach		Lowering of reservoir
Transitory applied stresses		Earthquake Wind	Machinery vibrations
Reduction in strength		Permafrost degradation Weathering Stress-induced fatigue	
Loading of the slope	Other landslides	Precipitation	Building materials

Process examples have been grouped into geomorphological, physical, and human processes following the classification of WG/WLI (1994). More comprehensive lists of landslide causes and triggers can be found in Varnes (1978), Cruden and Varnes (1996), and WG/WLI (1994).

2.3 STABILITY FACTORS

2.3.1 Material Strength and Topography

The inherent strength of material preconditions the stability of all slopes. Material strength determines both the height and angle that a slope can maintain against specific disturbing forces. The influence of material strength and slope geometry on slope stability can be inferred from spatial patterns of landslide distributions (e.g., Dai et al., 2011; Keefer, 2000; Roering et al., 2005) (Figure 2.4). These relationships allow, to a limited degree, determination of landslide susceptibility. Material type (e.g., soils, soft rock, or brittle

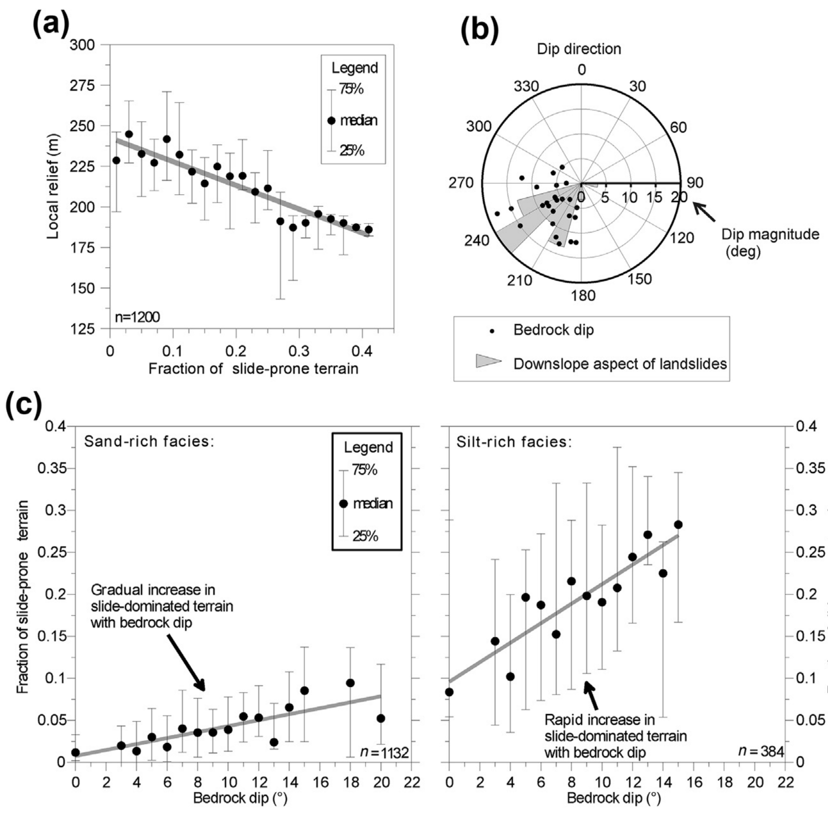

FIGURE 2.4 Example from part of the Oregon Coast Range, U.S.A., showing the relationships between geological and geomorphological conditions and landslide distribution. (a) Relationship between relief and landslide abundance in terrain prone to deep-seated landsliding; (b) Strong correspondence between bedding orientation and the failure of landslides; (c) Moderately strong relationship between landslide abundance and the angle of bedding for sand-rich terrain prone to deep-seated landsliding (left) and a stronger relationship for weaker, silt-rich sedimentary rocks (right). *Reproduced from Roering et al. (2005) with permission by the Geological Society of America.*

rock) and slope geometry also influence the type of landslide that may be expected (e.g., soil flow, slump, rock avalanche), and knowledge of these parameters can also be used to help predict the type of landslides expected (Cruden and Martin, 2013; Gerrard, 1994). Thus, knowledge of material type, slope geometry, and the orientation of structural features relative to slope aspect is essential for assessing slope stability.

Material strength is derived from the strength of the particles or crystals, the interparticle contact forces, the structure produced by fabric or discontinuities, and apparent cohesion provided by vegetation. Materials are traditionally divided into (indurated) rock and soils, the latter of which can be further subdivided into cohesive and noncohesive soils. Mohr−Coulomb strength parameters (friction and cohesion) are routinely assessed for each type of soil or rock present at a site; for the latter, it has been recognized that an equivalent Mohr−Coulomb failure criterion that incorporates the effects of discontinuities (e.g., joints) should be used (e.g., Hoek et al., 2002). In rock masses, discontinuity mapping usually involves quantifying the number, orientation, and strength of joints, faults, or bedding layers. In soils, it may be more appropriate to quantify the depth, orientation, strength, and permeability of distinct compositional units.

Discontinuities are perhaps the most important determinant of strength, particularly when dipping out of the slope. They arise from compositional changes (namely bedding or weathering horizons), or structural weaknesses such as cleavage, foliation, fractures, and faults. There are two main effects that discontinuities and compositional changes have on the stability of a slope:

1. They provide structural weaknesses below the (intact) strength of the uniform material, which may become preferential failure surfaces, particularly when planar. For example, the soft rock Tertiary landscapes of New Zealand host many thousands of large landslides; here it is the presence of clay layers, with very low frictional resistance, within the Tertiary sandstones and mudstones that result in landsliding on gently inclined dip slopes (Thomson, 1982). However, where bedding is horizontal or dipping into the slope, the Tertiary rocks can maintain steep cliffs, which is also due to a distinct lack of tectonic joints.
2. Discontinuities or compositional changes can allow pathways for water seepage or create permeability boundaries, both of which can influence the porewater conditions of the material and modify the slope stresses (Section 2.3.1).

A clear relationship between material strength, slope geometry, and landslide susceptibility may not always exist. For example, the largest landslide to develop in the greywacke of the Central Southern Alps of New Zealand occurs in a location with some of the highest rock mass strength. Here the 150−200 M m^3 Mueller Rockslide is inferred to have taken advantage of relatively planar bedding surfaces on the limb of a large anticline

(McColl and Davies, 2013). Elsewhere in the greywacke terrain, the folding and jointing are possibly too intense to permit very extensive failure surfaces to develop, and consequently the dominant mode of failure is rock fall. Furthermore, in an analysis of earthquake-induced landslide distributions arising from the 1989 Loma Prieta earthquake in California, Keefer (2000) demonstrated a complex relationship between material type and failure densities. Although the most indurated rocks generally had a lower density of landsliding than less indurated rocks, the least indurated rocks did not have the greatest number of landslides. As well as this, when ranked by estimated or measured shear strength parameters (rather than rock type) there was no statistically significant relationship with landslide density. Although part of the reason for the latter may be problems with the sampling resolution (Keefer, 2000), or variable unaccounted site effects (Section 2.3.4), it may also be partly explained by the concept of strength equilibrium slopes (*sensu* Selby, 1982). These are stable slopes in which the slope angle is in equilibrium with the present stress conditions and strength of that slope. This concept implies that stronger rock masses can attain and maintain steeper angles of slope than weaker rocks, and thus the steepest slopes in a landscape are commonly composed of the strongest rock and vice versa. Therefore, in a landscape dominated by strength equilibrium slopes, it is possible that all slopes have a similar FoS regardless of rock type or slope angle. An increase in slope stresses (or a reduction in material strength may be equally likely to lead to failure of any of these slopes.

One way to increase the slope stresses is through steepening or lengthening the slope. Slopes that have undergone erosional steepening are often said to be "oversteepened" (with respect to their strength equilibrium). A well-recognized process of natural slope steepening is by glacial erosion of valley sides; glacial oversteepening is a commonly recognized preparatory factor for instability of previously glaciated slopes. However, whether or not a slope is oversteepened will depend on its strength equilibrium, and Augustinus (1995) argued that this needs to be quantified to be able to make such a determination. By quantifying the rock mass strength of glaciated slopes in Fiordland, New Zealand, Augustinus (1995) found that most slopes are in strength equilibrium, and despite the glacial steepening, most slopes are not oversteepened. Slopes that were oversteepened were likely to have adjusted quickly back to strength equilibrium. Nevertheless, steepening of the slope can reduce stability. This makes the slope more prone to failure or a given trigger more likely to cause failure, ultimately reducing the life of the slope or the time before the slope will adjust (i.e., undergo failure) to reach a new strength equilibrium profile.

Independently, slope angle and material strength are not reliable predictors of stability; but, if both material strength (including the strength and orientation of discontinuities) and slope angle can be quantified and assessed together, then susceptibility determination can be powerful. These are the two basic parameters of all landslide susceptibility maps. Recent advances in remote sensing (e.g., satellite, airborne, and terrestrial distance ranging) have permitted very high resolution topographic models of slopes at various scales, which allow accurate measurements of slope gradient. Material strength is seldom directly quantified and assessed at a sufficient resolution to detect strength changes within geological units. Instead, most susceptibility maps distinguish between different rock types, rather than distinguishing strength variability within those rock types. This is because the input data usually come from geological maps rather than geotechnical maps and measuring the rock strength at a high spatial resolution is both difficult and expensive.

While the material strength, structure, and topography precondition all landslides and can be used to assess failure susceptibility (i.e., the spatial distribution of potential failures), they do not provide a useful way to predict the timing of those failures. For failure to occur, the FoS needs to drop. This may be caused by an increase in slope angle (considered above), but is most often due to either a decrease in the intrinsic strength or a gradual or sudden increase in an external stability factor. The rest of this chapter focuses on these time-dependent factors.

2.3.2 Intrinsic Strength Degradation

The intrinsic strength of a slope can reduce slowly over time as a result of alteration (weathering) of the slope materials or strain accumulation. The gradual loss of intrinsic strength, or strength degradation, is a phenomenon experienced by all slopes; therefore, there is potentially a lot to be gained from studying the processes involved. Despite its importance, strength degradation is perhaps the least understood of all landslide causes because it operates internally, making it difficult to observe and quantify. Because strength degradation operates in all slopes, it plays a fundamental role in controlling when a slope will fail. This role could be visualized in a model such as that of Figure 2.3, where the gradient of the time-varying stability line would influence the time that FoS = 1 is reached. In the absence of other external factors capable of triggering failure, strength degradation may itself eventually trigger failure. Most of the time, its role is probably to reduce stability, increasing the likelihood for triggering by other instability factors.

Strength degradation can involve any combination of a range of weathering processes, including those of chemical decomposition of materials or stress–strain processes involving the stress-induced growth of fractures or development of a failure surface. While it can operate without external stimuli or fluctuating conditions (e.g., rainfall-induced water pressure changes), the presence of water in a slope or the operation of external stresses may greatly increase the rate of strength degradation.

Strength degradation, or its various processes (e.g., static fatigue, permafrost degradation, weathering), have often been cited as the possible cause of failures that had no apparent trigger. Indeed, there are numerous failures that have occurred without any apparent trigger (Wieczorek and Jäger, 1996), even when the events have been witnessed (e.g., Hauser, 2002; Lipovsky et al., 2008). This is not to say that strength degradation is the only possible trigger for many of these slope failures; changes may occur in the slope by more commonly observed processes that have, for whatever reason, gone undetected or unrecognized, such as unmonitored seepage pressures. For example, recent analysis of temperature conditions by Allen and Huggel (2013) provides support for a plausible alternative hypothesis for the trigger of the 1991 Mt Cook Rock Avalanche in New Zealand, which had previously been cited as an example of a slope failure triggered by strength degradation, or more specifically, a drop in the intrinsic strength of the slope (Glade and Crozier, 2005; McSaveney, 2002; Petley, 2011). Allen and Huggel argued that the trigger was pressurized meltwater. The meltwater was generated during 4 days of extremely warm temperatures, which was then entrapped and pressurized behind seepage outlets that were blocked during two subsequent days of freezing conditions. While careful monitoring and scrutiny of processes may help to reveal the subtle triggers for landslides, strength degradation is no doubt an important process and likely to act as a trigger for some failures.

2.3.2.1 Stress-Induced Fatigue

Stress-induced fatigue encompasses all processes of stress-induced degradation in material strength that operate at stresses below the instantaneous ultimate failure strength of the material (e.g., Attewell and Farmer, 1973; Cruden, 1974; Lajtai and Schmidtke, 1986; Potyondy, 2007). It typically operates at the microscopic scale of interparticle forces and involves the nucleation and growth of fractures within brittle materials. Local failure is thought to be possible at stress magnitudes below the ultimate failure strength because of concentration of stresses around structural imperfections such as fractures; this phenomenon is referred to as subcritical fracture propagation. Within a perfectly homogenous and uniform mass of material, the stresses may be distributed approximately uniformly within the material. However, all materials contain microscopic imperfections and many rock masses are heterogeneous and contain fractures and joints arising from high-magnitude stresses (e.g., tectonic stresses in excess of the ultimate failure strength). In addition, rocks may exhibit unbalanced stresses that develop through rock-forming processes (e.g., cooling or burial) or secondary processes (e.g., tectonic stresses). These imperfections and stress imbalances result in stress concentrations. These concentrations can cause microfractures to nucleate, which further increases the nonhomogeneity of the stress distribution. The stresses become concentrated at fracture tips, causing fracture propagation and further stress concentration. This positive feedback loop can, in theory, involve a nonlinear (rapidly accelerating) increase in stress concentrations as fractures propagate and result in the catastrophic failure of a material.

Stress release fracturing can also occur from unloading of overburden or confining materials. This release of stress can induce stress reorientations, potentially leading to stress concentrations sufficient to cause fracture propagation. It is a process familiar in the mining and tunneling industries where high confining stresses exist and can be altered relatively quickly. In natural slopes the same process occurs, often operating over a longer time period owing to the larger scale of the situation and the longer time frames by which natural processes (erosion) unload the material. The exception to this may be the unloading induced by other mass movements, which can trigger stress release behind the release surface. Stress release fracturing may be important in priming or triggering failures in slopes that have undergone glacial erosion (McColl, 2012).

Static fatigue is the gradual damage to a material as a result of the constant application of stress; for slopes, this stress arises from the self-weight (gravity) stresses, in addition to any constant tectonic or internal/residual stresses. The steeper or higher a slope, the greater the self-weight stresses that are in operation. Thus, the steepening, loading, or heightening of a slope will likely facilitate faster rates of static fatigue. Pore fluids can also help facilitate stress-induced fracturing through chemical reactions at highly stressed fracture tips (this is referred to as stress corrosion). Because the positive feedback mechanism of stress fatigue causes an acceleration of fracture propagation, it may be possible for a slope to fail "out of the blue" with no apparent change in the slope conditions or external factors (e.g., change in slope angle, rainfall, or seismicity). Progressive failure mass movements in brittle materials are thought to involve a stress fatigue process, involving a strain-controlled development of a through-going failure surface from the coalescence of fractures (Petley et al., 2005) (Figure 2.5). This is a process that may operate without external stimuli, involving internal deformation of material, even while the global FoS remains above one. Progressive failures therefore may occur without any other apparent trigger. Petley et al. (2005) discussed how strain monitoring can be used to forecast the timing of progressive failures or failures that are undergoing accelerating creep; but, this relies on the strain being detected. Identifying potential failure sites before they show detectable strain or geomorphic signs of imminent slope failure (e.g., bulging or fractures) presents a greater challenge.

Cyclic fatigue involves the fatigue of materials in a fashion similar to that of static fatigue; but, instead of being static, the stresses acting on a material are temporally varying (cyclic) stresses. In slopes, cyclic stresses may arise from rapid ground motions produced during earthquakes or from vibrations induced by machinery or wind loading. Much lower frequency stress cycles could arise from any changes in the stresses operating in slopes, such as changes associated with water table fluctuations, thermal changes (e.g., Gischig et al., 2011), snow

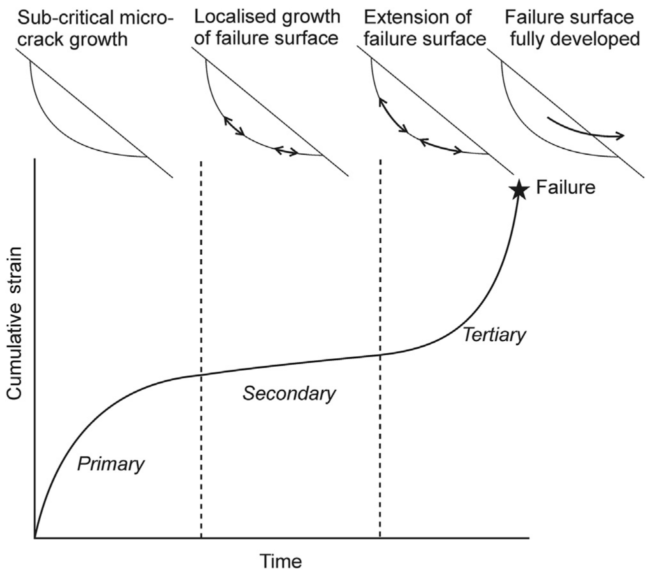

FIGURE 2.5 Schematic representation of the development of a through-going failure surface during the different stages of creep that govern progressive failure. *Based on Petley et al. (2005) and Froude (2011).*

or ice loading and unloading, changes in atmospheric pressure, and tidal forces. Experiments on (mostly nonrock) materials show the following:

1. The number of stress cycles a material can withstand is reduced with increasing levels of stress.
2. There tends to be a stress limit below which no amount of cycles will induce fatigue.

Because of the high-amplitude stress cycles produced by earthquake shaking, most research on cyclic fatigue in slopes has been studied with respect to earthquake ground motions (e.g., Moore et al., 2012). It is thought that repeated earthquake shaking, that does not cause outright failure, can weaken slopes and lead to failure during subsequent (and possibly smaller) earthquakes or as a result of other triggers that would not have otherwise been sufficient to cause failure (Hancox, 2010; Moore et al., 2012).

2.3.2.2 Chemical Weathering

The chemical alteration of rock and sediments can reduce the shear strength and equilibrium angle of slopes (Durgin, 1977). Chemical weathering is most rapid in warm humid (i.e., tropical) environments, but it occurs in all environments. A variety of chemical weathering processes can contribute to the reduction in material strength, for example, dissolution, hydrolysis, hydration, and oxidation. These processes may reduce material strength by weakening the intact particles or the contacts between particles (joints) or change the sensitivity of a material to water (e.g., through the production of some types of clay minerals). The state of weathering of a slope not only controls the stability of the slope but will also influence the type of landslide likely to occur as the structure of the slope material changes. Durgin (1977) related the degree of weathering in granitic rocks to the dominant types of landslides. For example, rock falls are most common on unweathered rocks, whereas debris flows become more prevalent once weathering has begun to disintegrate the rock granules, and completely weathered granites without any structural control host rotational failures (slumps). This slope strength dependence on weathering means that landslide susceptibility based on rock type alone may be misleading, especially because different rock types and rock masses weather at different rates. Indeed, Durgin (1977) described how granite rocks in some regions are relatively unweathered and provide the most stable (i.e., host the least landslides) of all rocks in that region, whereas in regions where chemical weathering is intense, granites can be the most prone to instabilities. The degree of weathering is thus an important factor to quantify. However, the relationship between chemical weathering and strength degradation is not necessarily straightforward. Fan et al. (1996) determined that the strength of fresh rocks with well-developed clay fabrics actually increased during initial weathering because of changes in fabric. Weathering-induced strength degradation did not occur until the sediments themselves were altered. It is also important to bear in mind that many initially cohesionless materials will also increase in strength as weathering progresses because of the additional cohesion provided by weathering products.

2.3.2.3 Cold Environment Processes

Permafrost degradation: In environments cold enough to undergo permanently freezing conditions (permafrost) or ground temperatures fluctuating above and below freezing, another mechanism of strength degradation can exist; one controlled by thawing of frozen groundwater. Frozen water within rock fractures and rock and soil pore spaces can increase shear strength. If this melts, as it may do in a warming climate, the drop in strength may be sufficient to trigger failure if one or both of the following conditions are met:

1. The stability of the slope had been lowered to an otherwise marginally stable state while the water was still frozen.
2. The meltwater within the materials became pressurized and lowered effective normal stresses on potential failure surfaces.

A growing body of empirical evidence suggests a link between warming temperatures, or extremes in warm temperatures, and the occurrence of slope failures (Allen and Huggel, 2013; Gruber and Haeberli, 2007). For rock slopes, Krautblatter et al. (2013) have developed an ice rock mechanical model to explain the loss in strength during thawing of permafrost; and notably, their model explains why permafrost degradation can trigger deep-seated rock slope failures as well as failures in the near surface. Interestingly, their model considers strength degradation arising from a combination of static fatigue, progressive failure, and a drop in the intrinsic (frictional) strength of rock and ice rock contacts.

Freeze–thaw processes: Weathering associated with repeated melting and refreezing of interstitial water has been recognized as another preparatory factor in jointed rock masses (Matsuoka and Murton, 2008). The expansion of water upon freezing (ice wedging), coupled with the movement of water toward the freezing front (ice segregation), can generate sufficient pressures to induce fracture propagation (Matsuoka and Murton, 2008; Selby, 1993). The possible intensification of freeze–thaw conditions during deglaciation may have led to more enhanced rock fall activity and talus development during early deglaciation (e.g., Rapp, 1960). Several researchers have suggested a link between freeze–thaw processes and modern rates of rock fall activity (Gruber et al., 2004; Matsuoka, 2008; Matsuoka and Sakai, 1999; Noetzli et al., 2003; Ravanel et al., 2010) and possibly even a link to large-scale rock slope failures (Davies et al., 2001; Wegmann and Gudmundsson, 1999).

2.3.2.4 Discussion

Every slope must undergo strength degradation during its life span. Strength degradation must therefore play a role in reducing the critical failure threshold required for a host of other more recognizable triggers or may itself be the final failure trigger. To that end, if strength degradation could be quantified accurately, along with the driving and resisting stresses operating for every slope, landslide predictions would become much more accurate. The reality is that we are far from achieving a robust understanding of strength degradation or a means to accurately predict its effect. Two of the limitations to understanding strength degradation are:

1. The difficulty of observing the processes involved and
2. The impracticality of knowing the entire history of the slope; the slope history influences the slope strength and existing stress conditions.

A fuller understanding and predictive capability may best be achieved by integrating various disciplinary approaches. For example, undertaking detailed engineering–geological mapping and strength testing (e.g., Brideau et al., 2009); using powerful numerical techniques to model progressive failure (e.g., modeling progressive failure; Eberhardt et al., 2004; Locat et al., 2013) or stress corrosion/static fatigue processes (e.g., Potyondy, 2007); using geophysical approaches, such as measuring the microseismicity generated by precursory fracture propagation (e.g., Amitrano et al., 2010; Spillmann et al., 2007) or repeat imaging of the material properties to assess reductions in strength through time (e.g., spectral analysis of earthquake ground motion; Moore et al., 2012). Synoptic models that attempt to incorporate a range of processes, such as that of Krautblatter et al. (2013) for permafrost degradation, hold promise for holistic strength degradation models in other types of environments. Because of its pervasive applicability, developing better predictive capability for strength degradation is arguably one of the greatest and potentially most fruitful challenges for slope stability research.

2.3.3 Groundwater Changes

Dynamic triggers are factors that are transient and bring a slope from a marginally stable state to failure or movement when they temporarily exceed the failure threshold. Changes in groundwater (and seismic ground accelerations discussed in the next section) are the most commonly recognized dynamic triggers. A useful point to keep in mind is that most slopes experience numerous dynamic events without undergoing failure, and it is not necessarily the largest of these that causes final failure. The effectiveness of those dynamic events in triggering failure depends not just on event magnitude but on the stability threshold, which can reduce through time as a result of other preparatory factors (e.g., strength degradation).

Groundwater fluctuations arise from either a change in the infiltration of water into a slope (e.g., from rainfall or snowmelt), from a volumetric change in porosity, or from a change in the drainage conditions of the slope (e.g., changes in seepage pressures or flooding at the base). Groundwater fluctuations can alter stability in the following ways:

1. Increased groundwater gradients induce flow or seepage within slope and this adds a driving force (e.g., drawdown following rapid lowering of lakes or reservoirs at the base of slopes).
2. Groundwater fluctuations influence porewater pressures, which change the effective normal stresses, and therefore the shear strength of potential failure surfaces.
2. Saturation of water can change the inherent strength of materials (e.g., saturation of soils and swelling clays).

The relationship between groundwater levels (or more often the magnitude or intensity of rainfall) has been investigated empirically, with the establishment of triggering thresholds, and deterministically using slope stability models.

Particularly for shallow landslides, rainfall is the most common source for groundwater fluctuations that trigger failure or movement (Van Asch et al., 1999). While good empirical relationships can be established between rainfall and triggering thresholds (Glade, 1998)—especially when antecedent soil moisture can be taken into account (Crozier, 1999)—the exact processes controlling these relationships remain uncertain. For example, where effective cohesion, rather than only the frictional properties of a soil, strongly influence stability, it may be peak moisture conditions rather than peak pore-water pressures that trigger failure (Hawke and McConchie, 2011). However, much of the uncertainty with rainfall thresholds arises from uncertainty in the infiltration, flow pathways, and drainage conditions in the slope. Surface topography, the topography of the failure surface (usually the bedrock–soil interface), and spatial variability in the permeability of the slope materials have a strong influence on the spatial relationship between rainfall and groundwater changes. For example, the confluence of water along the bedrock–soil interface of bedrock hollows or fossil gully features (colluvium-filled bedrock depressions) creates additional saturation of the materials, and consequently these are common slope failure sites (Crozier et al., 1990; Wilson and Dietrich, 1987). Although identifying and modeling the surface topography of a slope is relatively easy, the topography of the bedrock–soil interface is more difficult to characterize. Recent work has also shown that the bedrock–soil interface is not as impermeable as often assumed (Brönnimann et al., 2013). The underlying bedrock can store and release water into the soil during rainfall events, and thus may have a considerable influence on both the timing and distribution of soil saturation during a rainfall event. Perhaps the most recognized factor modifying the relationship between soil saturation and rainfall is the interception of rainfall and evapotranspiration provided by vegetation. Vegetation removal is perhaps the most common preparatory factor for the development of shallow landslides, through both loss of rainfall interception and apparent cohesion, and has been recognized as a major contributor to human-induced global soil erosion (Glade, 2003).

Failure or movement of deep-seated landslides is also influenced by rainfall patterns. However, in this case the slopes usually respond over longer timescales than the duration of individual rainfall events, instead responding to seasonal or longer term changes in rainfall or evaporative patterns. For large, slow-moving landslides, porewater pressure and movement are generally positively correlated. However, the advent of high-resolution surface and subsurface monitoring of movement and groundwater fluctuations has shown that this is not always the case. Other internal (e.g., strain hardening during shearing, or development of negative porewater pressures in zones of extension), geometrical, or nonfrictional (e.g., rheological) mechanics can modify or even reverse this relationship (Corominas et al., 2005; Massey et al., 2013; van Asch et al., 2009).

2.3.4 Ground Shaking

Seismic ground shaking or artificial sources of ground vibrations are another type of dynamic failure trigger. Earthquake shaking, as opposed to artificial sources, is the focus of this section because earthquakes are more capable of releasing seismic energy strong enough for slope failure (Figure 2.6). Three main ways exist that a slope failure can arise from earthquake shaking:

1. Sudden ground accelerations that induce instantaneous shear stresses in excess of the mobilized shear strength.
2. Cyclic fatigue-induced propagation of fractures, leading to formation of a failure surface.
3. Seismically induced increases in porewater pressures.

FIGURE 2.6 Example of earthquake-triggered slope failures. These rock avalanches, which failed high on the slopes above, and traveled on to, the Black Rapids Glacier, Alaska, were triggered by the 2002 Denali earthquake. *Photograph: Rod March, US Geological Survey.*

It is possible that more than one of these may operate during any earthquake. If only (2) and/or (3) operate, the failure may occur sometime after shaking has ceased (Jibson et al., 1994), and the effectiveness of both of these will depend on the duration as well as the intensity of shaking.

Despite general uncertainty in the specific processes governing earthquake-triggered failure, good relationships between earthquake magnitude and intensity and the density of landslides have been established for a number of earthquakes (Dai et al., 2011; Hancox et al., 2002; Keefer, 1984; Meunier et al., 2007). In general, the number of landslides reduces with distance from the epicenter, mimicking the attenuation of shaking intensity away from the epicenter; but, the specific spatial distribution depends on a number of other seismic site effects that operate in addition to the static factors influencing failure susceptibility. Ground accelerations also depend on a variety of potential seismic wave characteristics interacting with the unique geologic, structural, and topographic conditions at any given site (Aki, 1988; Alfaro et al., 2012; Buech, 2008; Geli et al., 1988; McColl et al., 2012; Meunier et al., 2008). Interestingly, weakened and fragmented material associated with existing or incipient landslides may even modify and amplify the shaking experienced on those parts of the slope (Burjánek et al., 2012; Moore et al., 2011). The hydrological conditions at the time will also influence the distribution of coseismic failures; a high groundwater table may lower the static FoS but may also mean that a smaller rise in groundwater, through seismic excitation, is required for failure.

2.4 SUMMARY AND CONCLUSION

The geological and geomorphological controls on slope failure (e.g., the type, strength and structure of material, and the slope geometry) play an important role in predisposing slopes to failure and controlling the likely spatial distribution of failures. These factors also largely determine which type of failures will occur and have a strong bearing on the threshold for stability on which other stability factors operate. Spatial analysis using GIS platforms helps to elucidate the strength of the relationships between various stability factors and landslide failure, and is a useful tool for calculating landslide susceptibility. However, even though it is possible to identify the slopes most likely to fail in a regional study, determining the frequency of slope failures on a regional scale is a considerably harder challenge. Even local-scale investigations of single slopes may not be sufficient to achieve this. Precisely predicting the movement patterns for closely-monitored, large, active landslides remains a challenge because of the time-dependent evolution of the stability factors. Many of the slopes investigated in a regional-scale assessment of susceptibility may share apparently similar predisposing factors; but, precisely which slopes will fail during any given period of time, or upon application of an external trigger, may lie beyond our capability of prediction without resorting to methods of statistical probability. Much of this uncertainty probably lies in the operation of the processes of strength degradation. This uncertainty will gradually be overcome through advances in knowledge, such as better recognition and investigation of the multitude of strength degradation processes, more methods becoming available and applied for observing, monitoring, and modeling slopes, and further attempts made to develop long-term time-dependent models of instability. These advances would potentially allow the quantification and useful application of stability models as proposed schematically in Figure 2.3.

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