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7.21 Mass-Movement Causes: Changes in Slope Angle

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Glossary

Debris avalanche A mass of rock fragments and soil that moves rapidly down a steep mountain slope.

Lahar A landslide of volcanic debris mixed with water, down the sides of a volcano.

Solifluction The slow, downhill movement of soil in areas typically underlain by frozen ground.

Tephra The fragmented solid material produced and ejected in the air by a volcanic eruption.

Abstract

This chapter discusses and illustrates how changes in slope angle can cause mass movement. Several processes can cause removal of lateral or underlying support of a slope, and most of the time multiple processes are acting together on a landscape. Slow and sudden processes causing changes in slope angle are differentiated, and several examples and illustrations of each are given. In addition, this chapter reviews current literature on landscape evolution modeling in which researchers try to incorporate these geomorphological processes in the analysis and simulation of current and future landscapes.

7.21.1 Introduction

Changes in slope angle can be a trigger for mass movement. Either a slope can become too steep for shear strength to balance shear stress so that the angle of repose is exceeded and mass movement occurs, or the slope becomes steep enough to reinforce another triggering mechanism decreasing shear strength or increasing shear stress (e.g., saturation with water; *see* Chapter 7.20). Several mechanisms are discussed and illustrated herein that can cause changes in slope angle, as well as the differentiation of processes that cause a slow or a sudden change in slope angle. Sometimes several processes work together to cause changes in slope angle, resulting in more complex interactions and feedback mechanisms between processes. In addition, current modeling efforts are reviewed, which deal with multiple processes causing changes in slope angle, typically in landscape-evolution models. Landscape evolution modeling is reviewed in Coulthard (2001), Pazzaglia (2003), and Tucker and Hancock (2010).

7.21.2 Slow Changes in Slope Angle

Several processes can cause slow removal of lateral or underlying support of a slope, and most of the time multiple processes are acting together on a landscape (Selby, 1993; Easterbrook, 1999; Huddart and Stott, 2010). Ultimately, combinations of tectonic uplift, the lowering of base level, sediment supply, water flow, or gravity drive rivers to incise in a landscape, thereby undercutting and slowly (over) steepening slopes (**Figure 1(a)**) (Bridge and Demicco, 2008). In addition, gradual erosion by water (surface runoff and gully erosion), wind erosion, weathering, and waves cutting cliffs on a shoreline can be causes of slow removal of lateral support and subsequent slope failure (**Figures 1(b)** and **1(c)**). Finally, pressure decrease or changes in groundwater (e.g., when a lake draws down slowly or a glacier melts) may also cause mass movement (**Figure 1(d)**). Many efforts in landscape evolution modeling are trying to simulate and understand better or more of these processes and their interactions, which is reviewed in Section 7.21.4.

7.21.3 Sudden Changes in Slope Angle

Different processes can cause a sudden change in slope angle and subsequent slope failure (e.g., Evans, 2004). The first process is mass movements themselves causing subsequent mass movements by changing slope angles (and hydrology) in and around the landslide scar and toe (**Figure 2(a)** and **2(b)**) (Claessens et al., 2007). Second, major discharge and extreme events including rapid incision, undercutting, and meander migration are possible processes causing slope angles to change (Huddart and Stott, 2010). Other examples include a

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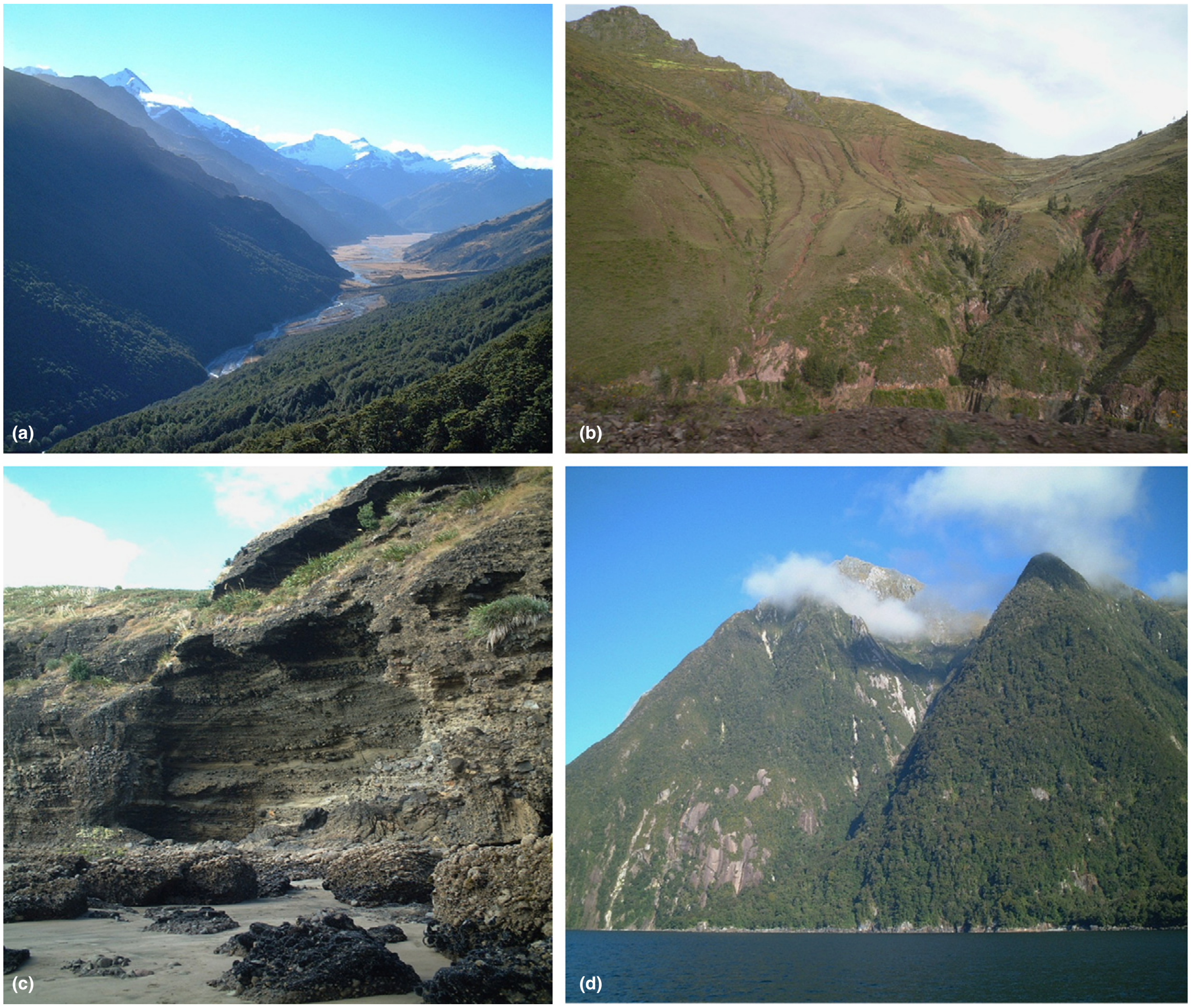

Figure 1 (a) A river incises into the landscape, slowly removing lateral support of the mountain slopes (Rees Valley, Wakatipu, New Zealand). (b) Severe water erosion (surface runoff and gullies) causing landslides (near Cuzco, Peru). (c) Wave-cut cliffs causing slope failure by removing lateral and underlying support (Waitakere Ranges, New Zealand). (d) Gradual dropping lake levels and glacier melting causing landslides by removal of lateral support and pressure (Milford Sound, New Zealand).

sudden drawdown of a lake, rapid melting or draining of a glacier, dropping water levels from a flood, or collapse of (limestone) caves and mines (**Figure 2(c)**). More rapid indirect processes include road construction, tectonics (earthquakes), and volcanic activity. The latter can realize sudden changes in slope angle and mass movements either associated with the eruption of a volcano itself or as a result of mobilization of very weak volcanic deposits such as tephras (ash, lapilli, and pieces of rock) (**Figure 2(d)**). Volcanic mass movements are generally referred to as lahars, debris avalanches, or flank collapses. To illustrate how mass movements change slope angles, Claessens et al. (2007) used the LAPSUS-LS (landscape process modelling at multidimensions and scales) model to simulate landslide hazards, erosion, and deposition patterns for a study area in New Zealand. The model was run for several consecutive yearly timesteps, and by comparing the different landslide hazard maps between the timesteps, they got insight into the pattern of upslope and downslope triggering of new landslides and the resulting slope retreat. **Figure 3** shows details of a comparative operation between the landslide hazard maps after timesteps 1 and 5. Higher hazards occur upslope of the failed slide because of undercutting and steepening of the slope above the eroded part. Furthermore, downslope of the failure parts with a higher landslide potential occur that are caused by steepening of local slopes mainly on the sides of the landslide sediment lobe. Because water from upslope is more canalized toward the steepened eroded part of the landslide, parts bordering the channel show less contributing area and are relieved of some failure potential. In this way, the model simulates the mosaic-like shifting pattern of upslope and downslope triggering of new landslides over the years by soil material redistribution and slope-angle changes caused by former mass movements.

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Figure 2 (a, b) Former landslides changing slope angles causing subsequent landslides (Peru and Ecuador). (c) Collapsed sea cave (Waitakere Ranges, New Zealand). (d) Intense gully erosion and landsliding in loose volcanic material (lapilli) (Mount Longonot, Kenya).

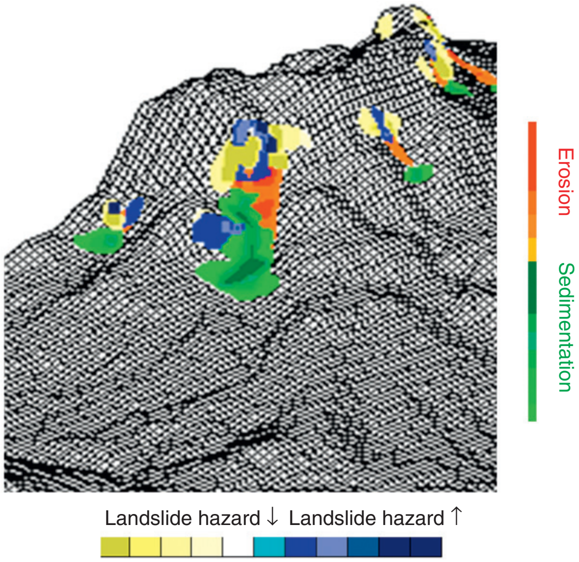

Figure 3 Comparison of landslide hazard maps between timesteps and visualization of resulting changed (in)stability patterns. Red colors indicate landslide erosion, whereas green colors are deposition; yellow colors signify a decreased landslide hazard; and blue colors an increased landslide hazard.

7.21.4 Changing Slope Angles in Landscape Evolution Models

Several efforts are ongoing in landscape evolution modeling that are trying to include one or several of the processes causing changes in slope angle described above and combine these with landslide modeling. Champel et al. (2002), for example, used a numerical model combining uplift, hillslope diffusion, and landsliding to show the dynamics of fault-related fold propagation in western Nepal. Coulthard et al. (2000) applied a cellular model with approximations for mass movement, creep, vegetation, hydrology, erosion, and deposition to an upland catchment in the UK to disentangle the effects of land use and climate change on channel formation. Dadson and Church (2005) studied the evolution of an idealized glaciated valley during the period following retreat of ice using a numerical model (including landsliding and fluvial sediment transport) with a numerical landscape evolution model that combines a detailed tectonic displacement field with a set of physically based geomorphic rules (including bedrock landsliding). Densmore et al. (1998) generated synthetic landscapes that closely resembled mountainous topography observed in the western US Basin and Range geomorphic province. Van Der Beek and Braun (1999)

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employed a numerical surface process model that included long-range fluvial transport, hillslope diffusion, and landsliding in order to quantitatively assess the tectonic, lithological, and structural controls on the landscape evolution and denudation history of the southeastern Australian highlands. Their results indicated that the observed highland morphology requires that the drainage divide be established at its present location prior to opening of the Tasman Sea; that escarpment retreat does not appear to be the fundamental process eroding the highlands; and that the observed barbed river drainage may be imprinted as a result of lithological variation. The LAPSUS modeling framework (Schoorl et al., 2002; Claessens et al., 2007) hosts separate modules for simulating overland flow, creep, solifluction, tillage erosion, and landsliding, all of which have process-based algorithms that make changes in slope angles over time. The combination of several processes in a general landscape evolution model, taking into account interactions and feedback mechanisms, is currently under progress.

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Biographical Sketch

Lieven Claessens has extensive experience in the spatial analysis and modeling of soil–landscape–land-use systems. At Wageningen University, he developed the LAPSUS-LS landscape process model, a spatially explicit methodology for predicting landslide hazard and quantifying associated soil redistribution (erosion–sedimentation). LAPSUS-LS forms part of the LAPSUS framework, a landscape evolution model simulating multiple processes (water erosion by runoff, tillage erosion, and landslide erosion) in the context of current and future environmental change. The model has been explicitly linked to methodologies addressing ecological processes and land-use changes to assess interactions and feedback mechanisms between landscape, land use, and landcover, and has been applied in study areas all over the world. In addition, he has experience in digital soil mapping, integrated assessments of agricultural systems, and land-use change modeling. His current research at CIP (International Potato Center) is focusing on interactions between biophysical and socioeconomic processes from household to regional scale levels. Within the Tradeoff Analysis (TOA) framework, case studies are conducted in Kenya, Uganda, Ethiopia, Peru, and Ecuador. Integrated assessments of the sustainability of the agricultural systems are performed with emphasis on testing adaptation strategies, specifically alternative technologies and policies in potato- and sweet potato-based systems, in the context of climate change.

Arnaud Temme works at Wageningen University in the Netherlands. He has experience in the dynamic spatial modeling of landscape and land-use change, working primarily in the conceptual and technical development of the LAPSUS model. He added process descriptions for soil creep, solifluction, and biological and frost weathering, as well as an algorithm for dealing with natural depressions to the LAPSUS framework. Working in South Africa, he studied late Quaternary landscape development using various stratigraphical and dating techniques and simulated the same development with several LAPSUS versions. He also worked on other landscapes in the Netherlands, Belgium, Poland, Spain, Croatia, and Turkey. In land-use change modeling, he developed a method to map the spatial distribution of agricultural land use of different intensities for the whole of Europe.

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Dr. Jeroen M. Schoorl is currently an assistant professor at the chair of Land Dynamics at Wageningen University (Netherlands). He has extensive experience in geomorphological modeling and characterization of integrated soil, landscape, and land-use systems. He carried out several international and national research projects on geomorphology and landscape–soil interactions in Europe (Spain, Greece, France, and Turkey) as well as some preliminary investigations in Latin America, Africa, and Asia. He has founded and currently leads the LAPSUS group, a team of researchers working at modeling landscape processes at multispatial and temporal dimensions and scales. In addition, he has experience with land-use change modeling and digital soil mapping. He has authored or co-authored over 68 papers in national and international proceedings, refereed journals, and books (28 peer reviewed).