Chapter 1 Introduction

Landslides present significant hazards to humans and the built environment, annually causing thousands of casualties and great financial loss worldwide. Increased groundwater pressure that reduces frictional shear resistance is a primary trigger of landslides. Efforts to forecast landslide location, timing, and mobility generally assume hydrostatic groundwater pressure along landslide bases, and forecasts often are inaccurate. This partly results from incomplete recognition of mechanisms by which groundwater alters hillslope materials, and of mechanisms by which groundwater pressure change may affect landslides or may be affected by landslide movement. Groundwater pressure also may vary during earthquakes but groundwater response in preexisting landslide shear boundaries to coseismic loading remains unknown. Improved prediction of landslide location, timing, and mobility also requires accurate knowledge of the groundwater distribution in landslide-prone materials, but methods by which such a distribution may be obtained are not well established. The studies that comprise this thesis attempt to address these problems. Two persistent, clayey landslides (Slumgullion in Colorado, USA and Two Towers in California, USA) typical of many worldwide and in Japan, notably on Shikoku Island and in Niigata Prefecture, were studied in the field and laboratory and through theoretical modeling. The pore-water and shear resistance response to simulated coseismic loading of material from two persistent landslides were studied in the laboratory. These landslides (Johnson Creek and Carmel Knoll) occur in Tertiary mudstone along the Oregon, USA coastline near the offshore Cascadia subduction zone, which essentially presents a mirror image to the Japan Trench subduction zone and parts of Japan’s coastline. Methods to model the distribution of groundwater perched within landslide-prone colluvial soils also were developed; landslides often occur in partly saturated colluvial soils throughout Japan and worldwide.

Chapter 2 Methodology

Landslides were mapped and conditions were continuously monitored at the persistent, clayey landslides for periods of days to decades. Monitoring of landslide motion included ground-based interferometric synthetic aperture radar (GBInSAR) and sensors installed at the ground surface or in boreholes. Other monitored conditions included groundwater pressures, horizontal soil stress, vertical soil deformation, soil water content, precipitation, snow depth, air pressure, and air temperature.

Samples were obtained of landslide materials and were tested in commercial laboratories and at Kyoto University. Parameters measured included density, moisture content, particle-size distribution, Atterberg limits, shear strength, inherent swell potential, and mineralogical composition. Advanced shear-strength testing at Kyoto University included subjecting specimens to various stress paths to failure, including simulated coseismic loading calculated from seismograms from the M 9, 2011 earthquake located off the coast of Tohoku, Japan.

Mathematical modeling was performed to evaluate observations from monitoring, predict landslide stability and mobility, and forecast locations of landslide-prone colluvium and colluvial groundwater across large areas.
Chapter 3 Landslide motion affected by long-term and short-term variability in groundwater conditions

Groundwater effects on movement of the Slumgullion landslide were studied using a GBInSAR system for 4 days during 2010 and results from a study of its movement during 1985-1990.

During the GBInSAR survey, the landslide was observed to temporarily increase speed by as much as 10 times following ~1 mm of rainfall. Mathematical modeling suggested that this rainfall caused reduced groundwater pressure and consequently decreased frictional shear resistance only to shallow depths along landslide lateral shear boundaries. This resulted in landslide acceleration.

The landslide moved during 2010 at 47% of its 1985-1990 speed. This likely was due to declining groundwater levels that caused decreases of hydrostatic groundwater pressures along the landslide base and of non-hydrostatic groundwater pressures along the landslide’s lateral shear boundaries. Groundwater level decline was inferred from meteorological monitoring that indicated that precipitation decreased by 15% and air temperature increased by ~2° C between 1990 and 2010.

Study results indicated that landslides can respond to groundwater pressure changes ~5 orders of magnitude smaller than hydrostatic pressures present along the landslide base, and that fluctuation of non-hydrostatic groundwater pressure along landslide lateral shear boundaries is sufficient to affect landslide speed.

Chapter 4 Effects of atmospheric tides on groundwater pressure and landslide motion

Atmospheric pressure effects on groundwater pressure and consequent landslide movement were studied using monitoring of the Slumgullion landslide, laboratory testing, and theoretical modeling.

The landslide was observed to accelerate during periods of low atmospheric tides and decelerate during periods of high tides. Theory was proposed to explain this observation, with damping and delay of atmospheric pressure fluctuations particularly while propagating through the saturated landslide body resulting in development of seepage forces during tidal pressure fluctuations tides that modified effective normal stress along the landslide base. These stress fluctuations caused variation of shear resistance and changes in landslide speed. A mathematical model for landslide stability was proposed that includes atmospheric pressure and resulting pressure at the landslide base. Model results well reflected monitoring observations.

Models proposed suggest a spectrum of hillslope response to atmospheric pressure fluctuation depending on landslide thickness, material, and groundwater depth. Models suggest that rapidly moving storm systems could elicit hillslope response similar to that from atmospheric tides.

Chapter 5 Shear-induced dilation effects on groundwater pressure and consequent restraint of landslide motion

Shear-induced dilation and consequent groundwater pressure decrease and shear-zone strengthening has been proposed as a mechanism restraining landslide motion, but field evidence has been lacking. This hypothesis was tested using monitoring of the Slumgullion landslide and laboratory and field testing.

The landslide was observed to accelerate following significant rainfall or snowmelt as groundwater pressures within the landslide body increased, but decreased along the landslide’s lateral shear boundary. Theoretical modeling using field and laboratory observations indicated that the timescale for groundwater movement was as much as 10 times slower than the
timescale of observed landslide deformation. Hence, dilative strengthening of landslide shear boundaries may explain slow, persistent motion of many landslides.

Chapter 6 Landslide motion modulated by soil swell pressure during periods of groundwater pressure elevation

The hypothesis was proposed that high normal stresses developed along landslide lateral shear boundaries from soil swelling during periods of higher groundwater might restrain landslide motion. This hypothesis was tested using monitoring of the Two Towers landslide, laboratory testing, and theoretical modeling.

The landslide was observed to reactivate seasonally and reach peak speeds at inconsistent groundwater pressure. Landslide material swelled vertically by ~3 cm and developed tens of kilopascal horizontal stress as it swelled during the rainy season. Laboratory tests indicated high inherent swell pressure of landslide material.

Mathematical modeling using field and laboratory observations and a standard slope-stability equation predicted landslide reactivation and peak landslide speed 3-6 months sooner than were observed. The stability equation was modified to account for observed soil swelling and predicted landslide reactivation and periods of peak speed nearly perfectly. Swell pressures contributed as much as 9% of total resistance along the landslide’s shear boundaries. Hence, swell pressure may substantially restrain many landslides, especially those with high content of expansive clay.

Chapter 7 Coseismic loading effects on groundwater pressure and shear resistance of existing landslides

The pore-water and shear-resistance responses of preexisting landslide shear zones to coseismic ground motion and other stress paths were studied using advanced laboratory testing at Kyoto University and specimens from the Johnson Creek and Carmel Knoll landslides. Results were used to develop new shear strength models and approaches for forecasting coseismic landslide movement.

Pore-water pressure changes were not observed during simulated coseismic loading. This might have resulted from the highly transient nature of applied stress variation, the low hydraulic conductivity of the shear-zone material, and sensor location adjacent to shear zones; pore-water response within existing landslide shear zones to coseismic loading remains unclear. New shear-resistance models and coseismic displacement estimation approaches generally well reproduced displacement observed during simulated coseismic loading tests; however, the approaches worked best when transient normal stress excursions were damped by an average of ~20%. This may indicate that transient normal stress excursions were partly supported by pore water.

Chapter 8 Modeling the spatial distribution of groundwater in landslide-prone soils

New rule-based empirical approaches were developed for modeling the distributions of colluvium and colluvial groundwater.

Model results correlated well with observed colluvium and groundwater depths. Results correlated better with the locations of historical landslides than did widely accepted theory, which proposes that landslides in the region studied correlate with the base of the regional aquifer. Improved correlation of landslide locations with model results indicated that the distribution of colluvial groundwater more strongly controls landslide occurrence.

Chapter 9 Discussion

The research presented in this thesis sought to better understand the degrees and mechanisms by which groundwater pressure variation elicits changes in landslide motion, to
examine how atmospheric pressure and coseismic shaking may affect groundwater pressure and landslide stability, and to examine how material change during shearing or wetting may control landslide timing and speed. To take advantage of this new understanding of the effects of groundwater on slope stability, methods were developed to model the distribution of landslide-prone colluvium and colluvial groundwater across large regions.

It was observed that even very large landslides can accelerate from seemingly negligible rainfall. Modeling suggested that such rainfall can increase groundwater pressures at shallow depths along landslide lateral shear boundaries and cause acceleration, in the absence of changing groundwater pressure along the landslide basal shear boundary. Also observed was that long-term decreases in precipitation and increased evapotranspiration probably caused lower groundwater levels that may have caused strengthening of landslide lateral shear boundaries and contributed to observed landslide slowing over two decades.

Landslide acceleration was observed to correlate with low atmospheric tides. Theory was proposed that atmospheric pressure decreases over short time periods may cause upward-directed seepage forces that can result in weakening of landslide shear boundaries and landslide acceleration. According to the theory, response to atmospheric pressure fluctuations largely depends on the composition and depth of landslides, and that rapidly moving pressure decreases associated with storms could trigger landslides and landslide acceleration.

Landslide acceleration was observed to correlate with increased groundwater pressure within the landslide body but decreased pressure along the landslide’s lateral shear boundary. Deceleration occurred contemporaneous with increasing pressure along the lateral shear boundary. It was proposed that these observations resulted from shear-induced dilation occurring more rapidly than groundwater movement and pressure equilibration, such that landslide shear boundaries strengthened and restrained landslide acceleration. Similar effects at other landslides are likely but depend on landslide deformation and groundwater movement timescales.

Landslide movement was observed to correlate poorly with increased groundwater levels. It was proposed that this resulted from development of high soil swell pressures along landslide lateral boundaries contemporaneous with groundwater level elevation and consequent reduction of shear resistance along the landslide base. Mathematical theory that included swell pressure predicted landslide movement that nearly exactly matched that observed, while standard theory that did not account for swell pressure erred by 3-6 months. Soil swelling may restrain many clayey landslides, with the degree to which it does so determined by soil composition, landslide geometry, and degree of seasonal groundwater level fluctuation.

Shear-zone specimens from existing landslides subjected to simulated coseismic loading were observed to produce no change in pore-water pressure. However, modeling to forecast displacement during simulated coseismic loading tests performed better when transient normal stress excursions were damped, suggesting that pore-water partly supported those excursions. The full response of groundwater within existing landslide shear zones to earthquake ground motions remains unclear.

Statistical modeling approaches developed using rules established with process understanding can well predict the occurrence of landslide-prone colluvial soils and groundwater within. The importance of such modeling was revealed by comparing results to the locations of historical landslides. Landslides occurred with much greater spatial density within areas forecast to have colluvial groundwater than within areas directly affected by seepage from the regional aquifer, which was long believed to be the primary mechanism triggering landslides in the region.
Chapter 10 Conclusions

Landslide speed can vary markedly during short time periods from very small changes in groundwater pressure along lateral shear boundaries, absent changes in pressure along landslide bases. Changes in groundwater level over long time periods can similarly affect shear resistance along lateral shear boundaries and contribute to landslide speed variation, contemporaneous with changes in hydrostatic groundwater pressures along landslide bases.

Atmospheric tides can result in variable shear resistance along landslide shear boundaries by developing seepage forces that modify effective normal stress. These fluctuations can cause changes in landslide speed and may trigger landslides. Similar rapid pressure changes associated with rapidly moving storms could cause similar responses.

Accelerated dilation of landslide shear zones during landslide acceleration can cause reduction of groundwater pressure within those zones, resulting in elevated shear resistance that restrains landslide motion. Landslide speed and composition largely determine the extent of such restraint.

Increased normal stress along landslide lateral shear boundaries during periods of elevated groundwater level can restrain landslide motion. For the studied landslide, this increased stress caused a ~9% increase in shear resistance along landslide shear boundaries and resulted in slower motion and months-later reactivation than would be expected from well-established theory.

Coseismic stress variation might be partly supported by groundwater within existing landslide shear zones and modify their frictional shear resistance. Such modification can affect resulting landslide motion.

Discontinuous, thin, landslide-prone soils and groundwater within can be well predicted using hybrid statistical/process-based approaches. Groundwater within such soils may better determine the locations of landslides than groundwater seepage from regional aquifers.