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Capturing landslide dynamics and hydrologic triggers using near-real-time monitoring

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ABSTRACT: Near-real-time monitoring of active landslides or landslide-prone hillslopes can provide immediate notification of landslide activity, as well as high-quality data sets for understanding the initiation and movement of landslides. Typical components of ground-based, near-real-time landslide monitoring systems include field sensors, data acquisition systems, remote telemetry, and software for base-station data processing and dissemination. For the last several decades, we have used these monitoring tools to investigate different landslide processes. Some of our field applications have determined the groundwater conditions controlling slow-moving landslides, detected 3-D displacements of large rock masses, and characterized the transient near-surface hydrology triggering shallow landsliding.

1 INTRODUCTION

Most landslide investigations are autopsies of inactive slides or inventories of past slope failures. Such studies, however, reveal little about the dynamics of active landslides. Reliable landslide warning systems require accurate short-term forecasts of landslide activity, which in turn demand a detailed understanding of current field conditions and a quantitative framework for interpreting those conditions. This knowledge is difficult to extract solely from landslide postmortem studies.

Real-time or near-real-time landslide monitoring can provide insight into the dynamics of landslide initiation and movement. In addition, this monitoring can provide immediate notification of landslide activity that may be critical to protecting lives and property. Displaying current landslide conditions on the Internet can be extremely valuable to a wide variety of end users, including emergency responders, land managers, geotechnical engineers, researchers, teachers, and the general public. These groups may have very different uses for near-real-time monitoring data. Near-real-time systems also tend to ensure high-quality data sets about landslide behavior by helping to maintain continuity of monitoring during critical periods. If the systems or field sensors malfunction, they can be quickly repaired to minimize data interruption. In addition, such systems tend to promote the evolution of better landslide monitoring by identifying the need for additional or different sensors to better detect changing field conditions. The resulting data sets are valuable for improved geotechnical designs or emergency actions aimed at mitigating landslide hazards. They are also crucial for advancing scientific understanding of active landslide behavior.

The term real-time monitoring has become common in many settings, from finance to computer performance to environmental conditions. However, remote monitoring systems are not truly real time; there is always some delay between sampling conditions and displaying those conditions to users. Here we use the term near-real-time monitoring to designate observations that are delayed slightly (typically minutes to hours) but still close enough in time to represent the current status of field conditions. The degree to which a remote system approaches real time depends on the frequency of 1) data sampling in the field, 2) data transmission, and 3) data updates available to users.

Near-real-time monitoring systems have been used throughout the world to detect or forecast landslide activity. In Hong Kong, the USA, and Brazil, regional warning systems have been operated to forecast conditions for rainfall-induced shallow landslides, using near-real-time rainfall observations (Finlay et al. 1997, Ortigao & Justi 2004, Wilson 2005, Chleborad et al. 2006). Frameworks for similar systems have been developed for mountainous regions of Italy, New Zealand, and Taiwan (Aleotti 2004, Chien-Yuan et al. 2005, Schmidt et al. 2007). Site-specific, near-real-time systems have been applied in many countries to monitor critical structures, such as dams, or hazardous landslides (e.g. Angeli et al. 1994, Berti et al. 2000, Husaini & Ratnasamy 2001, Froese & Moreno 2007). Since 1985, researchers with the U.S. Geological Survey (USGS) have used near-real-time monitoring systems for regional warning systems (Keefer et al. 1987, NOAA-USGS Debris Flow Task Force 2005) and for recording the dynamics of hazardous active landslides or landslide-prone hillslopes (e.g. Reid & LaHusen 1998, e.g. Baum et al. 2005).

In this paper, we discuss some of the design considerations and components typical of ground-based, site-specific, near-real-time landslide monitoring systems. We then discuss some USGS applications of such monitoring systems. Finally, we present three brief case studies that illustrate monitoring system configurations and that document landslide dynamics or hydrologic triggering in very different geologic settings. These studies include: 1) identifying the groundwater pressures controlling a slow-moving, coastal landslide, 2) detecting 3-D displacement of a large rock block using inexpensive GPS receivers, and 3) capturing the transient, rainstorm-induced, soil-moisture conditions triggering a shallow landslide.

2 COMPONENTS OF NEAR-REAL-TIME LANDSLIDE MONITORING SYSTEMS

2.1 *System design considerations*

The technologies used in ground-based, near-real-time landslide monitoring systems have evolved rapidly in recent years; the development of new sensors, low-cost methods of telemetry, and new software for data dissemination have made this type of monitoring readily available and affordable. However, there is no standard setup that will work for all landslide monitoring. The design and implementation of near-real-time systems depends on considerations that vary from site to site, including: 1) The end purpose of the monitoring. Systems for public safety often differ from those intended to record data for scientific research studies. Automated warning systems may need redundant field sensors, power supplies, and data serving computers to help ensure continuous operation during landslide triggering events. The desired frequency of data updating, i.e. how close to real time the system is, can be greatly influenced by the end purpose of the system. 2) The type of landslide to be monitored. Instrumentation techniques and sampling frequencies to detect rapid debris flows differ greatly from those used to monitor slow-moving landslides. Moreover, designs to monitor displacement of a currently active slide can differ from those monitoring the hydrologic conditions the might trigger future sliding. 3) The physical setting of the field site. Landslides in urban settings may have access to AC power and readily available telecommunications, whereas very remote sites may need multiple radio repeaters or satellite links to relay data to a secure base-station computer.

Although designs and configurations can vary considerably, most ground-based, near-real-time landslide monitoring systems have certain components in common. These include: 1) sensors on or within the landslide mass or landslide-prone area, 2) data acquisition systems to sample and control the sensors, 3) a communication system to relay data from the field to base-station computers or the Internet directly, and 4) software for data analysis and visualization. An example system configuration is shown in Figure 1. Below, we provide brief overviews of each component with an emphasis on techniques we have found successful in USGS landslide monitoring.

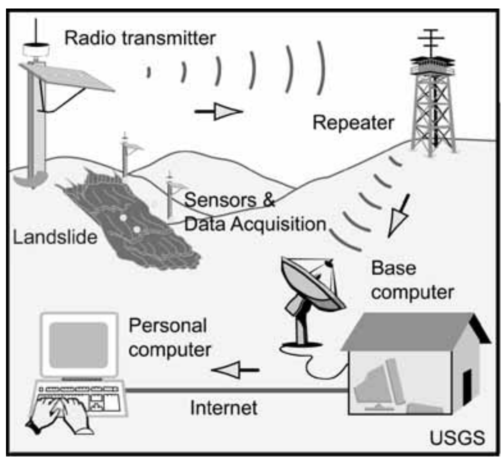

Figure 1. Example of a ground-based, near-real-time landslide monitoring system. Typical components include field sensors, field data acquisition system, remote communications (here via radio telemetry), data processing (on a base computer) and data dissemination (via the Internet).

2.2 *Field sensors*

For ground-based monitoring, detecting and measuring landslide activity typically requires an array of sensors placed on the ground surface and/or in the subsurface at the slide. For USGS monitoring, we have used both commercially available and USGS custom-built sensors. A wide variety of commercial-off-the-shelf electronic and/or mechanical geotechnical and hydrologic sensors exist (Dunnicliff 1993, Mikkelsen 1996). For remote sites, sensors need to be rugged, weather resistant, portable, and have low power consumption; power is often the most critical issue. Sensors also need to easily interface with data acquisition systems and have adequate sensitivity and resolution. Very-high precision instruments, common in scientific laboratories, are seldom needed for field monitoring. Instead, relatively inexpensive, yet precise, sensors are preferred because they may be destroyed by landslide activity. In addition, low-cost sensors can allow more units to be deployed. Often, sensor arrays with more complete spatial coverage, both on the ground and in the subsurface, are more useful than a few high-precision sensors.

Monitoring sensors typically provide two types of information: 1) actual displacement of a landslide or debris flow or 2) environmental conditions that affect slide activity. Slow-moving landslide displacement can be measured using surface or subsurface extensometers, tiltmeters, ultrasonic or laser distance meters, radar (Tarchi et al. 2005), digital cameras, videos cameras, or downhole inclinometers. Although surface cable extensometers are relatively inexpensive, they are particularly subject to disturbance by weather, animals, and local ground failure. Subsurface deformation can also be detected using grouted-in TDR (Time Domain Reflectometry) cables (Kane & Beck 1996). Measurements from Global Positioning System (GPS) receivers located on a slide can be processed relative to a known reference station to provide sub-cm positions and 3-D displacements (Kramer & Rutledg 2000, LaHusen & Reid 2000). Rapidly moving debris flows can be detected with tripwires, geophones, or flow-height sensors (LaHusen 2005).

Because most landslide and debris flow activity is triggered by hydrologic conditions, it is often important to detect changes in subsurface pore-water pressures. Furthermore, it may be desirable to understand the hydrologic processes modifying those pore pressures, including the infiltration of rainfall or snowmelt. Commonly used hydrologic sensors include precipitation gauges, tensiometers and dielectic soil-moisture probes for measuring unsaturated soil conditions, and piezometers for recording positive pore pressures. For automated recording, tensiometers and piezometers can be fitted with transducers for measuring fluid pressure. Piezometers can be directly buried in a sand pack, grouted in place (Mikkelsen & Green 2003), or installed in a cased borehole, whereas tensiometers and moisture sensors typically need direct soil contact.

2.3 *Data acquisition systems*

Remote sites usually require on-site data acquisition systems to power and control sensor sampling, log sensor data, and interact with the remote communication system. Site conditions and system configurations often dictate the number of data acquisition systems required; most systems can handle multiple sensors. Seismic and GPS instruments can require relatively high frequency sampling (0.1 to 100 Hz), whereas most geotechnical and hydrologic sensors are sampled at relatively low frequency (minutes to hours). USGS landslide monitoring has used both commercially available data loggers and USGS systems custom-developed for monitoring active volcanoes (Hadley & LaHusen 1995). A reliable power supply is an absolute necessity for each acquisition system, as well as for the remote communication system. We commonly use batteries and solar panels to supply power at remote sites; AC power is sometimes available at urban sites. For sites without AC power or adequate solar exposure, we often use air-alkaline batteries.

2.4 *Remote communications*

To provide near-real-time data updates from remote monitoring systems, some form of dependable communication system is needed. There are many options using either dedicated telemetry or commercially available services. Typically, the crucial link is between the remote monitoring stations and a secure base station with Internet access or a dedicated telephone line. This remote link can be provided by radio transceivers, satellite uplinks, or telephone services. The choice of a communication component depends, in part, on site remoteness, power availability, the frequency of data transmission desired, reliability, data throughput, and recurring expense. Low-power radio transceivers can use either a fixed frequency or license-free spread-spectrum technology, but line-of-site transmission may require repeater stations. Meteor burst radio communications can be used over long distances for low data-rate applications. Satellite uplinks may use a dedicated service such as GOES (Geostationary Operational Environmental Satellite). Commercial vendors can provide satellite phone modems or a fixed Internet address accessible through a low-cost VSAT (Very Small Aperture Terminal) satellite ground station. Although satellite uplinks may reach many remote areas, their transceivers can require more power than line-of-sight radios and their use can incur service charges. Telephone services, either land line, cellular or satellite, can be reliable options for low data-rate transmission.

However, they entail recurring service charges and may not be available at remote sites. For monitoring where close to real-time response and/or high data-rate transmissions are required, we often use dedicated radio telemetry. Importantly, battery-powered radio links are usually very reliable during stormy weather when landslides may be active. AC power or telephone communications may fail during these stormy periods.

2.5 *Data processing and dissemination*

After remote monitoring data are collected and relayed to a protected base-station computer, additional actions are needed to provide information to end users. Base-station computer actions typically include receiving the data, processing the data if needed, creating graphs and/or tables, and archiving the data. Remote data transmission may be controlled by the field acquisition system or by the base-station computer. There are a variety of software options for performing these tasks, including commercially available software packages, some using Open Process Control (OPC) protocols (http://opcfoundation.org), that can handle real-time data flow and processing. For many USGS systems, we use custom-written base-station software controlled by automated batch processing. Graphs can be generated, using commercial or license-free software, at specified intervals or in response to user requests. Once graphs and tables are created, they can be disseminated via a user's local computer network, or commonly, on web pages with public or password protected access. We typically use USGS web servers to disseminate monitoring information.

3 USGS APPLICATIONS OF NEAR-REAL-TIME LANDSLIDE MONITORING

Over the last several decades, researchers with the USGS have used monitoring systems to understand both the dynamic behavior of individual slides and the hydrologic conditions triggering widespread landsliding. Many of these efforts involved remote data acquisition and some invoked periodic transfer of data via cellular telephone service. (Ellis et al. 2002). USGS automated, near-real-time landslide monitoring sites are listed in Table 1 with a brief summary of their field sensors, data acquisition systems, and remote communication set-ups. Publicly accessible monitoring data from USGS systems currently in operation can be viewed at http://landslides.usgs.gov/monitoring.

Early USGS monitoring efforts at La Honda, California contributed to a San Francisco Bay regional landslide warning system that operated between 1985 and 1995 (Keefer et al. 1987, Wilson 2005). Here, near-real-time observations of rainfall, shallow pore pressures, and soil suction were transmitted using ALERT system radio telemetry. Starting in 1997, the Cleveland Corral landslide, threatening U.S. Highway 50 in California, was our first monitoring site with automated data dissemination via publicly accessible web pages on the Internet (Reid & LaHusen 1998, Reid et al. 2003). Since then, the USGS has operated many other near-real-time monitoring sites. With the exception of La Honda, all of the systems listed in Table 1 use or used USGS web servers to disseminate data over the Internet, typically with updates at a frequency similar to that of the listed data transmission. Our sampling, transmission, and update frequencies were selected to capture changes in the physical processes occurring in the field (e.g. movement, rain infiltration) while minimizing field station power usage. Sites with geophones, such as the Cleveland Corral landslide, scan data every second and transmit immediately if ground vibrations exceed a chosen threshold; thus these sites are closer to true real-time monitoring. USGS researchers have also played key roles in designing and installing near-real-time landslide monitoring systems to monitor alpine debris-flow activity in Italy (Berti et al. 2000) and volcanic debris flows at Ruapehu Volcano in New Zealand.

Below, we briefly present three USGS case studies using near-real-time monitoring that illustrate some of the advantages and complexities involved. Each study examines a different type of slide, uses different monitoring instrumentation and communication telemetry, and addresses different scientific questions. In particular, we focus on how near-real-time monitoring provides crucial insight into different landslide triggering and behavior. Each of the three cases is located near the Pacific Coast of the USA (Fig. 2) where rainfall-induced landslide activity occurs primarily during the winter/spring-wet season. Brand names for sensors and data acquisition systems are provided for descriptive purposes only and do not imply endorsement by the USGS; other vendors can provide similar equipment.

3.1 *Case study 1: Identifying groundwater controls on the motion of a slow-moving landslide, Newport, Oregon*

Most landslide movement is activated or reactivated by increased pore-water pressures acting on a slide's slip surface (Terzaghi 1950, Sidle & Ochiai 2006). These pressure increases can result from many processes. (e.g. Reid & Iverson 1992, e.g. Iverson 2000); understanding the timing and pathways of subsurface water flow leading to landslide movement is crucial to forecasting future slide behavior, developing warning strategies, and designing effective mitigation measures. Our first brief case study illustrates the use

Table 1. USGS near-real-time landslide monitoring sites.

Location and period of operation	Type of slide	Field sensors	Data acquisition system***	Communication system and transmission frequency
La Honda, California (1985–1995)	Shallow earth slide**	Rain gauges, piezometers, tensiometers, extensometers	Sierra Misco ALERT system	Radio network with repeater (15 minutes)
Cleveland Corral landslide, U.S. Highway 50, California (1997-present)	Translational earth slide	Rain gauges, geophones, piezometers, extensometers	USGS custom system	Radio network with repeater (15 minutes)
Woodway, Washington (1997–2006)	Rotational debris slide	Rain gauge, piezometers, extensometers	Campbell CR10X data logger	Telephone (15 minutes)
Rio Nido, California (1998–2001)	Earth slide	Rain gauge, geophones, piezometers, extensometers	USGS custom system	Radio network with repeater (10 minutes)
Headscarp of Mission Peak landslide, Fremont, California (1998-present)*	Rock block slide	L1-GPS receivers, extensometers, air temperature sensor	Environmental Cellular initially, then USGS custom system	Cellular telephone initially, then spread-spectrum radio network (30 minutes or hourly)
Edmonds, Washington (2001–2006)*	Shallow translational earth slide**	Rain gauges, soil tempera-ure probe, soil-moisture profilers, tensiometers, piezometers	Campbell CR10X data logger	Radio network (hourly and 15 minutes)
Everett, Washington (2001-2006)	Shallow earth slide**	Rain gauge, water-content reflectometers, piezometers	Campbell CR10X data logger	Radio network (hourly and 15 minutes)
State Route 20, Newhalem, Washington (2004–2005)	Rock block slide	Geophones, tiltmeters, extensometers	USGS custom system	Radio network repeater with (15 minutes)
Johnson Creek landslide, Newport, Oregon (2004-present)*	Translational slide	Rain gauge, downhole extensometers, piezome-ters, soil-moisture sensors, air and ground temperature sensors	Campbell CR10X data logger	Cellular telephone (daily)
Florida River landslide, Durango, Colorado (2005-present)	Ancient translational slide and recent debris slides in wildfire burn area	Rain gauge, extensometers, tiltmeters, piezometers, air temperature sensor	Campbell CR1000 and CR200 data loggers with radio network	Cellular telephone (hourly)
Ferguson rockslide, near Yosemite Natl. Park, California (2006-present)	Rock block slide	L1-GPS receivers, geophones	USGS custom system	Spread-spectrum radio network with repeater (hourly)
Portland, Oregon (2006-present)	Shallow earth slide**	Rain gauges, tensiometers, piezometers, soil-moisture sensors	Campbell CR1000 data logger	Cellular telephone (15 minutes)

*Monitoring at this site is discussed further in a case study.
**Instruments monitor(ed) hydrologic conditions in landslide-prone hillslope. Slide occurred at end of monitoring at Edmonds site.
***Brand names are provided for descriptive purposes only and do not imply endorsement by the USGS.

Figure 2. Map of western USA showing the locations of our three case studies (Newport, Fremont, Edmonds) illustrating near-real-time landslide monitoring.

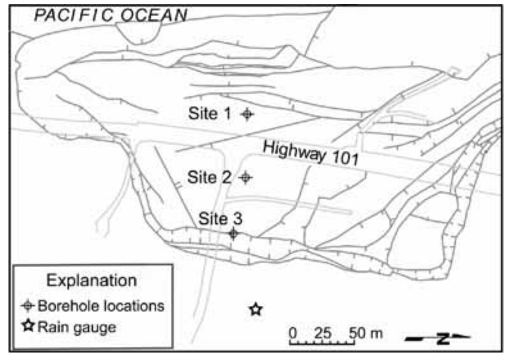

Figure 3. Map of the Johnson Creek landslide showing major structural features, location of rain gauge, and the three sites of grouped instrumentation boreholes. Slide motion is west towards the Pacific Ocean. Modified from Landslide Technology (2004).

of near-real-time monitoring at a slow-moving landslide to identify the relations between rainfall, pore pressure, and slide movement.

3.1.1 *Background and setting*

Many large, episodically active landslides disrupt U.S. Highway 101, the major north-south transportation corridor that links towns along the Pacific Ocean coast of Oregon, USA. The Johnson Creek landslide, near Newport, Oregon, has a history of repeated movements during winter rainy seasons, and frequently impacts the highway. This translational slide, about 200 m long, 360 m wide, and 26 m thick, occurs in seaward dipping (15–20°) siltstone, sandstone, mudstone and tuffaceous claystone of the Astoria Formation and is located on a nearly flat Pleistocene marine terrace. Total landslide displacement is about 28 m horizontal and 6 m vertical. (Priest et al. 2006). The largest recent movement episode occurred between January 2002 and February 2003, when the central part of the slide moved about 25 cm horizontally and dropped several cm vertically. (Landslide Technology 2004).

3.1.2 *Near-real-time monitoring*

Beginning in November 2004, the USGS installed near-real-time monitoring at this site, in cooperation with the Oregon Department of Geology and Mineral Industries and the Oregon Department of Transportation. Our efforts were focused on understanding the subsurface pore pressures controlling movement as well as the timing of and processes creating elevated pore pressures on the basal slip surface. Earlier investigators installed a rain gauge and pairs of borings at three sites along a longitudinal section of the slide (Fig. 3). At each site, a vibrating-wire piezometer (Slope Indicator) had been installed just above the slide plane in one boring and inclinometer casing in the companion boring. Wire-rope extensometers, anchored beneath the landslide's basal slip surface had also been installed in the inclinometer borings. (Landslide Technology 2004). We added electronic cable extensometers (Celesco) to the down-hole, wire-rope extensometer cables for automated recording. In November 2006, we installed two vertical arrays of six vibrating-wire piezometers each (Slope Indicator) between depths of 3 m and 26 m at sites 1 and 2 within the central and upper parts of the landslide (Fig. 3) so that both the lateral and vertical distribution of pore pressures could be monitored. These were installed in grout and are capable of measuring unsaturated soil suctions as well as positive pore pressures. We also installed two sets of dielectric soil-moisture content sensors (Decagon Devices) at shallow depths of 1.5 m and 3 m at sites 1 and 3 to assess the contribution of vertical rainfall infiltration to pore pressure changes at depth within the slide (Schulz & Ellis 2007). Two data loggers (Campbell Scientific), powered by batteries and solar panels, record data in 15-minute intervals. These data are transmitted automatically every 24 hours using cellular-telephone telemetry, graphed on a USGS base-station computer, and placed on a USGS website for viewing.

3.1.3 *Results*

Our monitoring between 2004 and 2007 (Ellis et al. 2007), spanning both dry and wet years, showed that basal-shear pore pressures begin to increase within just a few hours following rainfall events. Monitoring also indicated that landslide movement initiates when pore pressures exceed a threshold, with some minor variability (Fig. 4). Our monitoring also shows that rainfall-induced pore-pressure increases travel from near the headscarp (site 3) westward toward the toe of the slide (site 1), and that the travel time of the pore-pressure pulses decreases significantly with increased antecedent pore-pressure conditions (Fig. 4). Following rainstorms, there are almost simultaneous increases in pore pressures at all depths within each vertical array of piezometers located beneath the water table while shallower unsaturated zone responses lag (Fig. 5). This suggests that rapid pore-pressure increases at depth within the slide do not result directly from vertical infiltration of rainfall, but are likely due to lateral pore-pressure response from the headscarp graben area. Our observations demonstrate that enhanced forecasting of slow-moving landslide activity requires detailed knowledge of the links between pore-pressure response and movement, and that inferences based on other landslide studies may be inadequate. Near-real-time monitoring can provide the required information.

3.2 *Case study 2: Detecting 3-D movement using inexpensive GPS receivers, Fremont, California*

Predicting the timing of rapid, catastrophic failure of landslides and rockslides is a long sought after goal of landslide science (e.g. Saito 1965, Varnes 1983, Voight 1989). Most forecasting approaches rely on detecting the acceleration associated with a transition

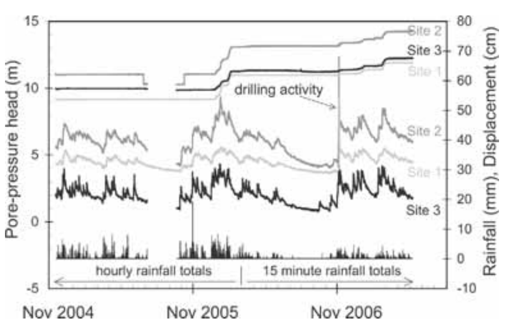

Figure 4. Basal shear zone pore-pressure head, rainfall, and landslide movement (from downhole extensometers) at the Johnson Creek landslide between November 2004 and May 2007. Site locations are shown in Figure 3.

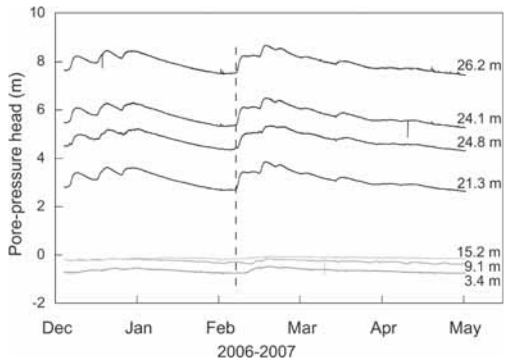

Figure 5. Pore-pressure head at various depths in the Johnson Creek landslide at site 1 between December 2006 and May 2007. Grey lines represent negative pore pressures from three different depths in the unsaturated zone; black lines represent pore pressures at four different depths in the saturated zone. Vertical dashed line shows timing of similar response in the saturated zone; response is delayed in the unsaturated zone.

from slow creep to rapid movement. For some failures, the timing of rapid movement can be predicted by projecting the trend of 1/velocity (Fukuzono 1990, Petley et al. 2002, Petley et al. 2005). Thus, detecting slide displacement in near real time is crucial to most forecasting efforts. The following brief case study examines the use of inexpensive, single-frequency (L1) GPS receivers to detect the 3-D displacement of a large rock block having the potential to fail rapidly.

3.2.1 *Background and setting*

More than 75, 000 ancient and dormant landslides are scattered throughout the hills of the San Francisco Bay region, California, USA (Pike 1997). During the wet, El Niño influenced winter and spring of 1998, the large (35 hectare) Mission Peak landslide reactivated, and moved more than 5 m (Geolith Consultants 2000). The slip surface of this 1.2 km long, 30–55 m thick, historically dormant earthflow is primarily in the clay-rich Orinda Formation (Geolith Consultants 2000). The reactivated slide is a small part of a much larger ancient landslide complex located above the City of Fremont in a tectonically active region, with on-going vertical uplift. Near the head of the slide, the seismically active Mission Fault crosses the slope. Upslope of this fault, the steep (45°) headscarp is composed of relatively competent Briones Sandstone (Graymer et al. 1995) that dips backward into the slope and contains several persistent joint sets. The headscarp area shows geomorphic evidence of prior large massive rock block failures (Fig. 6), as well as small sackung features, suggesting that both slow and rapid movements are possible in this setting.

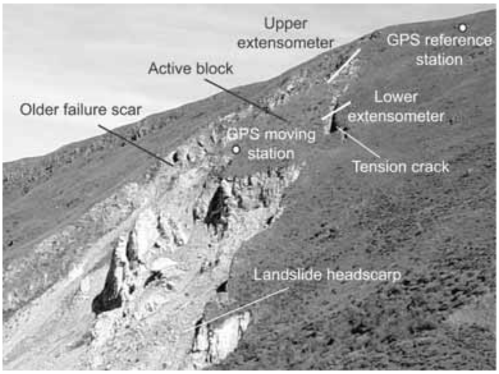

Figure 6. Photograph of active rock mass in headscarp of the Mission Peak landslide, showing large tension crack and adjacent older failure scar. Locations of two extensometers and two GPS stations also shown. Photo: Phil Stoffer, USGS.

In March 1998, the main earthflow was active and threatened homes at the toe of slide. During this time, we observed disturbance of a pre-existing, prominent tension crack (previously open about 1.5 m) in the headscarp area (Fig. 6). Our quadrilateral measurements of 3-D displacement across the crack showed continued movement and prompted concerns about potential catastrophic failure of a large rock block, partially bordered by this tension crack. The estimated volume of this block ranges between 50,000 and 170,000 m^3, depending on inferred thickness (Geolith Consultants 2000). Rapid failure of the remaining entire rock mass might result in a rockfall avalanche. Subsequent analyses of such an avalanche show potential maximum runouts of about 500 m along slope (Jurasius 2002).

3.2.2 *Near-real-time monitoring*

USGS monitoring at this site focuses on measuring surface displacement of rock in the headscarp region where acceleration might be a possible precursor to rapid failure. Over time, our monitoring tools have evolved to better identify the 3-D strain across the entire rock block as well as the time history of movement. Initially in March 1998, we used manually surveyed quadrilateral monuments located across the large tension crack. Over the next several months, we installed two surface cable extensometers (UniMeasure) to record downslope displacement across tension cracks (Fig. 6), first using a data logger (Campbell Scientific) and later using cell-phone communications (Environmental Cellular).

We then developed a low-cost, single-frequency (L1) GPS receiver system designed for automated data acquisition, rapid deployment, and prolonged operation in remote hazardous areas (LaHusen & Reid 2000). In February 2000, we installed a working prototype of this system in the headscarp area, using NovAtel GPS receivers, Micropulse GPS antennas, and a USSG-designed data acquisition and controller system. To obtain sub-cm measurements, we utilize very short baseline, static differential processing of GPS observations from two antenna/receiver stations, one located on the moving rock block and another located off the block, about 67 m away. Power for these two remote stations is supplied by solar panels and batteries. The GPS antenna on the moving rock mass is located near the outer edge of the block (Fig. 6), just upslope of the headscarp, to measure strain across the entire block (relative to the stable GPS receiver) and to increase the likelihood of detecting a rapid failure. Instead of continuously operating the GPS receivers, which use significant power, we employ a novel scheme of powering the receivers on and off with a variable duty cycle controlled by base-station computer software. Typically, we collect 30 minutes of GPS observations at 10-second intervals, transmit these data using 900 MHz spread-spectrum radio transceivers, and then power down the system for the next 30 minutes. Independent, high-precision, static GPS solutions, with fixed ambiguity resolutions, for each 30-minute observation period are automatically computed on the base-station computer using GPS processing software (Waypoint). Results are then automatically graphed and placed on a USGS website for viewing.

3.2.3 *Results*

Although our monitoring between 1998 and 2007 did not record rapid, catastrophic failure, it did demonstrate the ability of our L1-only GPS system to detect 3-D, sub-cm movement and accelerations of the rock mass during wet seasons. More than 40 cm of downslope motion of the block, measured by our lower extensometer crossing the large tension crack prior to installation of the GPS system, occurred during the wet 1998 season. Subsequently, between 2000 and 2007 our differential GPS system showed long-term northward, westward, and downward creep of the block, resolved into 3-D components in Figure 7. Creep might be expected because the GPS antenna is located near the headscarp free face. During the relatively wet springs of 2000 and 2006, the block accelerated slightly but then slowed during the following summers (Fig. 7). It did not exhibit creep to rapid failure. Nevertheless, our observations indicate that significant movement of the block is related to wet years or sequential wet years.

When the block was active during the spring of 2000, we measured movement with both extensometers and the differential GPS system (Fig. 8). The upper extensometer recorded about 5 cm of downslope

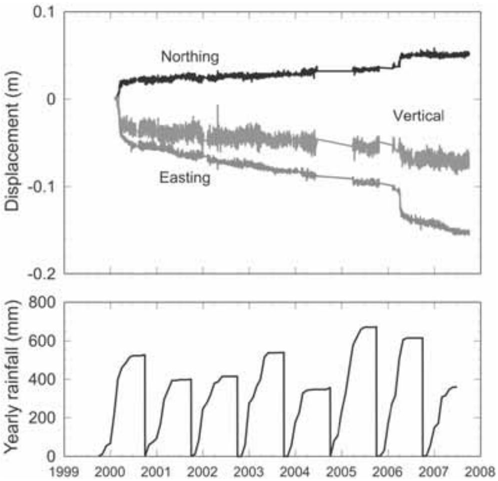

Figure 7. 3-D components (northing, easting, and vertical) of the high-precision, differential GPS solutions for the Mission Peak active rock block between February 2000 and September 2007. Points shown are 5-point medians of the independent static solutions for each 30-minute satellite observation period. Cumulative displacement is since installation in 2000; overall the block is moving northward, westward, and downward. Cumulative yearly rain begins October 1 of each water year.

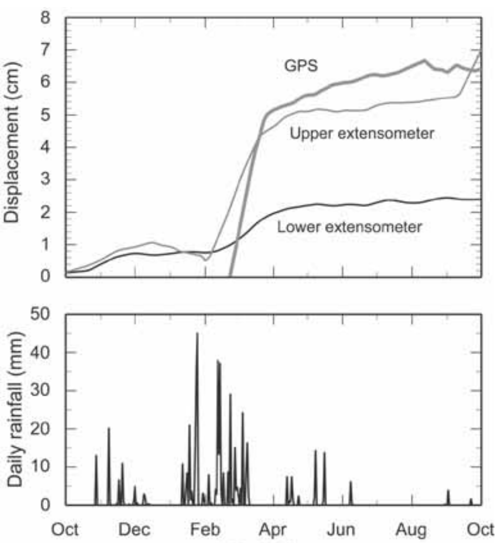

Figure 8. Daily rainfall, extensometer and GPS displacement measurements at Mission Peak during the 1999-2000 wet season. Extensometers have cables oriented downslope; therefore smoothed GPS displacement is computed along slope using the 3-D components. GPS data start in February 2000.

movement, the lower extensometer about 2 cm, and the GPS about 6 cm of cumulative slope displacement. Detrended GPS solutions have a standard deviation of about 2 mm in the horizontal and 4 mm in the vertical. Our monitoring illustrates the advantage of using high-precision GPS position solutions to detect 3-D strain across larger areas than can be readily measured using extensometers.

3.3 *Case study 3: Capturing shallow landsliding triggered by rainstorms, Edmonds, Washington*

Shallow landslides and accompanying debris flows pose a frequent and often devastating hazard worldwide (Iverson et al. 1997, Jakob & Hungr 2005, Sidle & Ochiai 2006). These slides typically occur in thin colluvium and are often induced by intense rainstorms or rapidly melting snow. Although such occurrences are exceedingly common, well-documented field examples of the subsurface hydrologic conditions controlling slide initiation are rare. Some studies have demonstrated that transient positive pore pressures in shallow saturated zones trigger failure (e.g. Sidle & Swanson 1982, Reid et al. 1988), whereas others have inferred that suction changes in unsaturated materials might instigate failure (e.g. Wolle & Hachich 1989, Collins & Znidarcic 2004). Understanding the near-surface transient hydrologic conditions controlling shallow failure is crucial to developing reliable forecasting or warning systems. In our final brief case study, we illustrate how near-real-time monitoring can identify the transient, shallow subsurface hydrologic conditions triggering a shallow landslide.

3.3.1 *Background and setting*

Shallow, rapidly moving landslides occur almost every winter along steeper sections (45–60°) of the coastal bluffs of Puget Sound between Seattle and Everett, Washington, USA (Baum et al. 2000). Although most of these slides are less than 1000 m^3 (Baum et al. 2000), they pose a continuing threat to public safety in this area, including disruption of a railway at the base of the bluffs and destruction of homes, other structures, and utilities on the bluffs. Rainstorm events producing one or more landslides have an average recurrence of six times per year (Chleborad et al. 2006). In cooperation with the Burlington Northern Santa Fe (BNSF) Railway, we selected a coastal bluff near Edmonds, Washington (20 km north of Seattle) for detailed monitoring of subsurface hydrologic conditions (Fig. 9). The purpose of our monitoring in this area was not to provide warning of individual landslides, but rather to determine when subsurface conditions are wet enough to make the slopes highly susceptible to landslides. During heavy rains in 1996–1997, several shallow landslides occurred near this site in weathered glacial deposits and colluvium (Baum et al. 2000). The 50-m-high bluff that we selected for monitoring is underlain by subhorizontally bedded glacial and interglacial sediments. A 3-m-thick layer of glacial till caps the bluff; beneath the till is a layer of glacial advance outwash that overlies dense glaciolacustrine silt (Minard 1983). Mechanical weathering of the dense, uniform, medium outwash sand produces a loose sandy colluvium mantle that covers much of the lower bluff.

3.3.2 *Near-real-time monitoring*

USGS monitoring at this site, which operated on AC power, focused on identifying the transient subsurface hydrologic conditions triggering shallow failure. We experimented with various kinds of sensors here in an effort to find a combination that provided hydrologic monitoring data of sufficient quality, reliability, and relevance to be suitable for forecasting landslide activity (Baum et al. 2005). Between September 2003 and January 2006, our remote station at the Edmonds site was equipped with sensors to monitor both unsaturated and saturated volumetric soil-moisture contents and pore-water pressure or suction (Fig. 9). We installed two adjacent tipping bucket rain gauges, two water-content profilers (Sentek EnviroSMART) equipped with eight (soil capacitance) sensors each at depths ranging from 20 cm to 200 cm, and two nests of six tensiometers (Soil Moisture Equipment Corp.), ranging in depth from 20 cm to 150 cm, to measure soil suction (Baum et al. 2005). The soil-water instruments were installed in dense glacial outwash sand and colluvium about 25–35 m above sea level (Fig. 9). Data were relayed every hour using line-of-sight radio telemetry to a server at Meteor Communications, then received, reduced, and graphed on a USGS base-station computer, and finally placed on a USGS website for viewing.

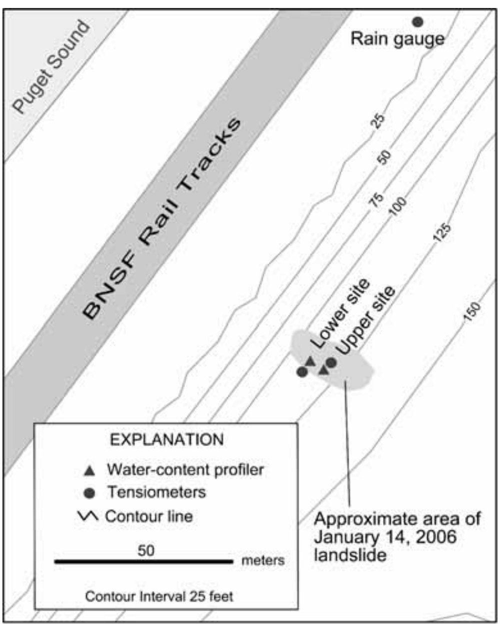

Figure 9. Map of Edmonds monitoring site near Seattle, Washington showing instrument locations and extent of January 2006 shallow landslide.

3.3.3 *Results*

On January 14, 2006, a shallow landslide occurred at the Edmonds site, destroying much of the instrumentation. However, we measured the near-surface hydrologic conditions through the previous three wet seasons and just prior to failure. Our near-real-time monitoring revealed several relations between rainfall, soil moisture, pore pressure, and the occurrence of shallow landslides in the Seattle area, including: 1) The timing and magnitude of soil moisture/pore pressure response from rainfall is highly dependent on antecedent soil moisture. For example, during October 2003, the soil was dry and wetting fronts moved slowly in response to rainfall (Fig. 10). As soil wetness increased throughout the winter season, pore pressure and soil wetness at depth responded much more rapidly to heavy rainfall. For example, heavy rainfall in mid-October produced an increase in soil moisture at 2 m depth after 6 days, whereas in mid-November, heavy rainfall resulted in a similar increase after only 1 day (Fig. 10). 2) The pattern of soil-moisture response was consistent with vertical downward infiltration,

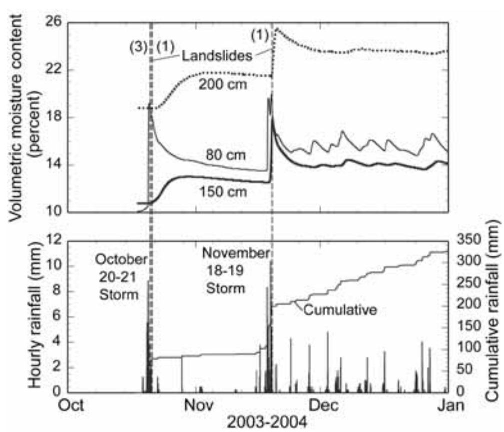

Figure 10. Soil-moisture response to rainfall at the Edmonds site between October 2003 and January 2004. Sensor depths (cm) are indicated next to response curves. Numbers of landslides that occurred on each date are indicated in parenthesis beside dashed vertical lines.

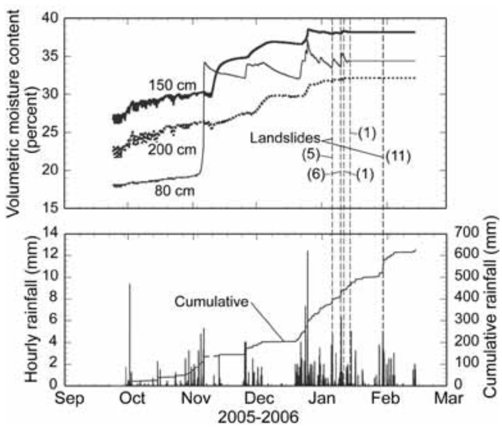

Figure 11. Soil-moisture response to rainfall at the Edmonds site between October 2005 and January 2006. A shallow landslide destroyed the instrumentation on January 14, 2006. Numbers of landslides that occurred on each date are indicated in parenthesis beside dashed vertical lines.

rather than lateral flow. 3) Landslide occurrence was strongly correlated to wet antecedent soil conditions. Intense rainfall that occurred in October 2003, November 2003, and November 2005 (Fig. 11) caused very few landslides because soil was relatively dry prior to these storms. However, storms of moderate intensity during January 2006, when soil was relatively moist after many successive days of rainfall, caused moderate numbers of landslides, even though the rainfall did not exceed our empirical rainfall threshold. (Baum et al. 2005, Godt et al. 2006). After several weeks of rain, the landslide at our monitoring site occurred during light rainfall on January 14, 2006 (Fig. 11), when overall soil moisture was at the highest since the beginning of the 2005–06 rainy season. Overall, our monitoring illustrates that soil-moisture conditions exert a strong control over the timing of shallow landsliding. The ability to measure these conditions in near real time makes it possible to determine when heavy rainfall is likely to cause landslides.

4 CONCLUSIONS

Near-real-time systems for monitoring active landslides or landslide-prone hillslopes have advanced rapidly in recent years and offer many advantages for understanding landslide processes. They can provide current information about remote landslide conditions, help ensure high-quality data sets, and capture transient and dynamic processes. Their configurations vary widely depending on the style of landsliding being monitored and the end purpose of the monitoring system, however most ground-based systems are composed of field sensors, field data acquisition systems, remote communications, and base-station data processing and dissemination, often over the Internet. We have used near-real-time monitoring to understand the dynamic behavior and hydrologic conditions triggering different types of landslides. Our investigations include identifying the groundwater conditions controlling slow-moving landslides, detecting 3-D displacements of large rock masses, and documenting the transient near-surface hydrology triggering shallow landsliding. Knowledge of both current field conditions and likely future behavior are crucial to developing better landslide forecasting and warning systems. Near-real-time monitoring systems can provide the current field conditions, but more work is needed on techniques to rapidly forecast future landslide behavior based on these near-real-time observations.

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