REMOTE SENSING OBSERVATIONS OF LANDSLIDES AND GROUND DEFORMATION FROM THE 2004 NIIGATA KEN CHUETSU EARTHQUAKE

ELLEN RATHJE(i), ROBERT KAYEN(ii) and KYU-SEOK WOO(iii)

ABSTRACT

In recent years, major developments in remote sensing have made it possible to use these technologies to document the effects of earthquakes. Specifically, high-resolution satellite imagery and three-dimensional laser scanning (LIDAR) can provide important observations of earthquake damage that supplement traditional observations from field reconnaissance. The 2004 Niigata Ken Chuetsu earthquake provided an opportunity to use remote sensing to document the distribution of landslides in the epicentral region through the use of high-resolution satellite imagery and to document the detailed three-dimensional geometries of several failures using LIDAR. The satellite imagery was acquired the day after the earthquake, but at very large acquisition angles that resulted in image distortion. Nonetheless, the satellite imagery accurately identified the landslide distribution in the epicentral region, although the total area of landslides was underestimated by about 25% as compared with traditional aerial reconnaissance because of the large acquisition angle for the satellite imagery. Terrestrial LIDAR was used to collect three-dimensional data at several failure sites, including two large rock slides and a railroad tunnel portal affected by ground deformation. The LIDAR data allowed for precise measurement of failure deformations and geometries, and provided digital terrain models that could be archived and used in future analyses. In the future, satellite imagery and LIDAR, as well as other remote sensing technologies, will play an increasing role in documenting and understanding the effects of earthquakes.

Key words: case history, deformation, earthquake damage, landslide, remote sensing (IGC: C1/E6)

INTRODUCTION

Remote sensing represents the acquisition of physical data using sensors not in direct physical contact with the area being investigated. Over the last few decades airborne and spaceborne remote sensing observations have played a key role in studies of large-scale earth science phenomena, such as tectonics, global warming, and volcanism, but they have not often been used by the engineering community because of their low spatial resolution (30 m or larger). However, with the launch of high-resolution instruments and the development of more advanced processing algorithms, remote sensing can now play a larger role in engineering studies, such as earthquake reconnaissance.

This paper focuses on two remote sensing technologies, high-resolution satellite imagery and three-dimensional laser scanning (LIDAR), and their use in documenting landslides and ground deformation from the 2004 Niigata Ken Chuetsu earthquake. During several weeks in November 2004, two reconnaissance teams funded by the Earthquake Engineering Research Institute (EERI) and the Geo-Engineering Earthquake Reconnaissance (GEER) Association visited the area affected by the earthquake. Each reconnaissance team was equipped with a terrestrial LIDAR unit for imaging important failures, and the second reconnaissance team also possessed high-resolution satellite imagery of the landslide region. The following sections provide an overview of the earthquake-induced landslides, the basic concepts regarding satellite imagery and LIDAR scanning for earthquake reconnaissance, and remote sensing-based observations of earthquake damage from the 2004 Niigata Ken Chuetsu earthquake.

EARTHQUAKE-INDUCED LANDSLIDES

The Niigata Ken Chuetsu earthquake (Mw = 6.6) occurred at 5:56 p.m. local time in a mountainous region in the central part of Niigata Prefecture. The earthquake occurred at a depth of 16 km on a blind thrust fault dipping to the west. The most pervasive effects of the earthquake were landslides and ground deformation in the upland region of the epicentral area. The area on the
Fig. 1. Quickbird satellite image of affected area in central Niigata Prefecture, Japan, including the tracks of ground reconnaissance

hanging-wall block directly above the fault rupture, in the vicinity of the Uonuma hills east of Ojiya and north of Kawaguchi (Fig. 1), is steep terrain that produced most of the triggered landslides. The earthquake produced very high levels of ground motion, including two sites that recorded peak horizontal ground accelerations between 1.3 and 1.8 g and several other sites that recorded peak accelerations greater than 0.3 g. A Japan Meteorological Agency (JMA) strong motion station was located in the town of Yamakoshi, which is situated in the center of the landslide region. This station recorded peak horizontal ground accelerations of 0.55 g (NS) and 0.74 g (EW), and a peak vertical acceleration of 1.08 g.

Most of the landslides in the Uonuma hills were relatively shallow (≤2 m deep), slope-parallel failures of residual soils mantling slopes or colluvium filled hollows. In addition, several deep-seated failures occurred, some of which had depths of several tens to more than 100 meters. Some of the triggered landslides blocked streams and impounded small to large reservoirs, and others destroyed entire upland villages (Kieffer et al., 2006).

Initial landslide concentrations and densities were estimated for the hardest hit areas of the Uonuma hills using a landslide inventory map (scale 1:30,000) that was based on aerial photographs acquired the day after the earthquake (Kieffer et al., 2006). This inventory, created by the Japan Geographical Survey Institute (GSI, 2004), includes large landslides and those smaller landslides where enough vegetation was stripped away to render the landslide observable from aerial photographs. Thus, this inventory represents a subset of the landslides observable from the ground. This partial inventory shows very high landslide concentrations, with concentrations as large as 30 landslides/km² in the area of greatest landslide activity near Yamakoshi (Kieffer et al., 2006). The partial area of land covered by landslides (i.e., landslide density) was also quite large in the area around Yamakoshi, with some 1-km² cells having as much as 35% of the ground surface covered by landslides (Kieffer et al., 2006).

BASIC CONCEPTS OF REMOTE SENSING

Satellite imagery and LIDAR represent fundamentally different remote sensing technologies that provide data at different scales and dimensions, yet both offer opportunities to develop more comprehensive and detailed observations of earthquake damage. Satellite imagery provides a two-dimensional image of the affected area hours to days after the earthquake, which can be used to document the locations and spatial distribution of failures across a large region. LIDAR provides three-dimensional data of the ground surface, which can be used to develop detailed morphologies of the most heavily damaged areas.

With higher resolution and improved data quality, comes less aerial coverage. Figure 2 provides a qualitative comparison of different optical satellite sensors and LIDAR instruments in terms of the aerial coverage and data resolution/quality. The lowest resolution satellites (LANDSAT, SPOT) provide the largest aerial coverage (in terms of scene size), such that fewer scenes and less
data can be used to evaluate the overall effects of an earthquake over a large area. However, these satellite images are not detailed enough to generate comprehensive damage data. The high resolution satellites (IKONOS, Quickbird, OrbView-3) provide more detailed data at higher resolution, but because of the smaller aerial coverage (~100 km² per scene) it is difficult and expensive to obtain high-resolution imagery over the entire area affected by an earthquake, which might encompass hundreds or thousands of square kilometers. Airborne LIDAR can generate thorough three-dimensional digital terrain models over large to moderate areas (1–100 km² per day), but at significant cost due to tasking of the aircraft and processing of the data. Finally, terrestrial tripod-mounted LIDAR can provide the most detailed, three-dimensional digital terrain models of failures, but it requires significant time if the failure extends over a large area.

Based on the comparisons in Fig. 2, it is clear that there is a considerable trade-off between data resolution/quality and aerial coverage. Thus, a multi-level approach is required in which larger scale data are used to develop large-scale observations of damage and smaller scale data are used to document the most important failures. Observations from different scales can be fused together to develop more comprehensive assessments of failure mechanisms and effects. However, much work is required before the use of these new technologies and the fusion of their data become commonplace in earthquake engineering. For the Niigata Ken Chuetsu earthquake, efforts were focused on using high-resolution satellite imagery to document the landslide/ground failure distribution in the upland areas and using terrestrial LIDAR to develop digital terrain models for some of the most dramatic and important failures. The basic issues related to data acquisition, data products, and data analysis for these two remote sensing technologies are discussed in detail below.

**Satellite Imagery**

Optical satellite imagery represents reflected or emitted electromagnetic energy at different wavelengths within the electromagnetic spectrum. Multispectral sensors on these satellites collect data in distinct spectral bands over a range of wavelengths that spans beyond the visible portion of the spectrum. The number of bands, range of wavelengths, and spatial resolution are selected for the sensor based on the primary application for the collected data. The high-resolution optical sensors that have been recently launched include IKONOS in 1999, Quickbird in 2000, and OrbView-3 in 2003. Each of these satellites carry sensors that collect panchromatic data (a single band between 450–900 nm, usually displayed as grayscale) at high resolution (0.6 to 1.0 m), as well as multispectral data at lower resolution (2.8 to 4.0 m). The multispectral sensors collect data in distinct spectral bands (blue 450–520 nm, green 520–600 nm, red 630–690 nm, near infrared 760–900 nm) that provide important spectral information about an image. Although the multispectral data are collected at a lower resolution, they can be fused with the higher resolution panchromatic data to produce spatially enhanced color images, called pan-sharpened images.

In addition to displaying the pan-sharpened bands as a true color representation of the scene for visual examination, the remotely sensed digital satellite data can be analyzed using image processing techniques to identify various features of interest. Image processing algorithms such as thematic classification and change detection, as well as simple visual examination, have been used to identify patterns of earthquake-induced urban damage (e.g., Saito et al., 2004; Yamazaki et al., 2004; Rathje et al., 2006). Satellite imagery is georeferenced to standard cartographic projections, such that remote sensing observations can be overlain with pertinent geologic maps, topographic maps, etc. to evaluate relationships between earthquake damage and these important conditions.

Each of the high-resolution satellites is located in a sun-synchronous orbit, requires cloud-free conditions for quality imagery to be acquired, and can be pointed towards an area of interest by rolling the sensor by up to about 50° from vertical. Although the acquisition of data off-nadir (nadir = vertical acquisition, off-nadir = non-vertical acquisition) increases the opportunity to collect data soon after an earthquake, larger acquisition angles distort the imagery. To minimize distortion, acquisition angles less than 15° are ideal. However, the revisit time over an area depends the acquisition angle; the revisit time can be as long as 11 days for acquisition angles less than 15° and areas near the equator, or as short as 2 days for acquisition angles between 15° and 25° and areas at a latitude of 80° (DigitalGlobe, 2005).

Figure 3 displays samples of pan-sharpened Quickbird imagery from the 2003 Bam, Iran earthquake (pre-earthquake data) and from the Niigata Ken Chuetsu earthquake (post-earthquake data, undamaged area). The imagery from Bam was acquired at an angle of 10° off-nadir, while the Niigata imagery was acquired at an angle of 47° off-nadir. It is clear that the structures in the Niigata image are heavily distorted with the sides of buildings clearly visible. The Niigata image also appears very blurry due to the distortion. Thus, this imagery cannot be used to evaluate urban damage patterns.
Terrestrial LIDAR Imagery

LIDAR imagery is produced by collecting the reflected and backscattered light from the active illumination of the ground using a laser source. LIDAR is a natural extension of laser range finder systems or electronic distance meters (EDMs) used commonly in survey applications. With LIDAR technology, a laser beam scans up and down and back and forth to acquire the precise distance to objects across the scene. The laser repeatedly shoots out a pulse of light at each rotation point of the scanner, with the pulse hitting the object and scattering a portion of the light back. By timing the round trip of each laser pulse, the range is determined for each scan position and a series of spherical coordinates are recorded based on the position of micro-stepper motors in the unit. Knowing the position and orientation of the instrument, a group of x, y, z coordinates (referred to as a “point cloud”) is acquired at a very rapid rate. As the scanning laser shots bounce off objects at various distances from the scanner, point measurements are collected that define the object’s shape. In addition, many LIDAR systems record the natural color of the objects as well as the intensity of returned laser light from each shot.

Terrestrial LIDAR systems used for earthquake reconnaissance are designed to be portable and optimized for the rapid acquisition of high-resolution three-dimensional imagery under outdoor lighting conditions. The maximum distance to targets that the laser can image ranges from several hundred meters to over a kilometer, depending on the manufacturer of the instrument, the model of instrument, the atmospheric conditions during the investigation, and the reflectivity of the target. The minimum target distance is 2 m. The intensity of the reflected laser light diminishes with distance and with the reflectivity of the target. The intensity of the returned beam is commonly recorded by the laser system and useful for identifying GPS- or survey-position targets placed in the field. The range accuracy of LIDAR distance measurements are between 0.3 cm and 2.5 cm at most ranges, depending on the model of instrument used. The laser beam divergence angle of the USGS LIDAR unit used during reconnaissance (Riegl z210i) is 3 milliradians, meaning that at a range of 10 m, the beam footprint is approximately 3 cm across. At a range of 100 meters, the beam footprint expands to 30 cm across. Because of the footprint size, the shots are ideally spaced 3 milliradians apart. The position of the center of the footprint is measured to a precision of 0.17 milliradians by the encoder. The angular position of the laser-pulse leaving the scanner is controlled by precise servo-motors within the units. Terrestrial LIDAR scanners make millions of individual x, y, z position measurements, at rates of up to 8,000 points/second.

To image a surface, the scanner is transported to the site in a travel-case or backpack. The USGS unit weighs 13 kg plus additional accessory cables, tripod, battery and laptop. The scanners are placed on a tripod either on the ground or on the roof of a vehicle in front of the

because of the image distortion. In contrast, the Bam image is very crisp and the structures do not show any major distortion, making it useful as the baseline data for change detection analyses that identify earthquake damage (e.g., Rathje et al., 2005).

Fig. 3. Pan-sharpened Quickbird imagery of undamaged urban areas from (a) Bam, Iran earthquake (10° acquisition angle) and (b) Niigata Ken Chuetsu earthquake (47° acquisition angle): Imagery courtesy of DigitalGlobe
object of interest (Fig. 4).

LIDAR cannot see behind objects, and so the first surface encountered casts a shadow over objects behind it. For example, in a scan of an embankment failure near the town of Horinouchi (Fig. 5), the near-field objects cast shadows over the debris located behind them (Fig. 5(b)). As the grazing-angle of the laser point decreases, proportionally larger shadows are cast on the ground behind the target. To minimize shadow zones and get full coverage of the target surface, the scanner is moved to other locations surrounding the target zone. Multiple setups limit the number of shadow zones while also increasing the resolution of the target shape and the outermost boundaries of the scanned area.

A typical LIDAR data set consists of many millions of data points. Efficient manipulation of that data is performed on computers with the highest currently available processing speed, maximized dynamic RAM memory, and a video card with a 128 MB or 256 MB memory buffer. The manipulation of so many points also requires specialized surface modeling software. Most laser manufacturers either distribute or suggest a specialized software program that is coupled with the laser. The USGS system utilizes a surface modeling software package called I-SITE Studio (I-Site Pty. Ltd., 2005). The software collects both the scan point-cloud data and can process multiple scans into georeferenced surfaces. After data are acquired, a series of standard processing steps is followed to produce a surface model. First, the multiple scans are either locally or absolutely georeferenced to one-another. A least squares “best-fit” match is made between scans, and can be augmented by precise survey measurements made with a total station or differential GPS (e.g., real time kinematic RTK-GPS, or Omnistar

Fig. 4. The USGS LIDAR unit (Riegl z210i) mounted on a tripod: For efficiency, roof mounted scanning allows for rapid movement and set up between scans, increasing the daily data collection by as much as an order of magnitude

Processing Procedures

Fig. 5. Processing procedures for ground-LIDAR technology: (a) scan target from multiple locations (e.g., 1,2), (b) register multiple scans 1 (left) and 2 (right) to reduce shadows (plan view), (c) render a solid surface model (oblique view with locations of scans 1 and 2) and (d) close-up oblique view used to measure specific landslide blocks and deformations: Data from failure along Route 252 near Horinouchi (37.1756N, 138.8434E)
HP-differential GPS). Filters are then used to eliminate unwanted data. For example, filters can be used to remove vegetation so as to observe the bare earth. The filtered point-data can then be “segmented” to differentiate discrete surfaces from each other and from complex objects like trees and brush. Surfaces can be used as working digital terrain models (DTMs) representing ground topography or as surface patches representing parts of various infrastructure objects. Again, different surface modeling schemes can be used to render surfaces from multiple scans. Multiple processed surfaces can be fused into a new composite surface model. The surface model can be used to document the condition of the ground and provide a baseline for change detection of volumes, areas, and distances.

OBSERVATIONS FROM SATELLITE IMAGERY

Both Quickbird and IKONOS collected satellite imagery data of the upland area affected by the earthquake the day after the earthquake (October 24, 2004). The Quickbird imagery was purchased and received within about two weeks of the earthquake, and was taken into the field on a laptop computer by the second reconnaissance team. However, the team did not use the imagery a great deal during reconnaissance because it was difficult to view the full image on a laptop computer monitor and the laptop could not be used easily in the field. Thus, after the GSI landslide map was obtained, it was preferred over the satellite imagery while in the field. Without that map, the satellite imagery might have been more useful, particularly if it had been printed out as a large-scale map before traveling to the field.

The Quickbird image was acquired at 47° off-nadir with the sensor pointed to the west to capture the affected area, while the IKONOS image was acquired at 32° off-nadir with the sensor pointed to the east to capture the affected area. The images were acquired at such large angles because of the adverse orbital locations of the satellites relative to Japan the day after the earthquake. As previously discussed, large acquisition angles result in image distortion, which is most pronounced for tall objects and mountainous terrain. For the Niigata Ken Chuetsu earthquake, the acquisition angles were so large as to conceal the far side of some ridges. Additionally, because the Quickbird sensor was pointed to the west to capture imagery of the affected area, the Quickbird image tends to overestimate the size of the landslides facing east and underestimate the size of landslides facing west. On the other hand, the IKONOS sensor was pointed to the east to acquire imagery over the affected area, such that west-facing landslides are overestimated and east-facing landslides are underestimated.

Figure 6 is the post-earthquake Quickbird image of the upland Uonuma hills area affected by the earthquake. Figure 6 includes a highlighted region south of
Table 1. Geologic units in study region

<table>
<thead>
<tr>
<th>Age</th>
<th>Geologic unit</th>
<th>Description (Yanagisawa et al., 1986)</th>
<th>Area within study region (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleistocene</td>
<td>Uonuma (Uₙ)</td>
<td>Marine silt and sand</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>Wanazu (W)</td>
<td>Sandstone</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td>Shirolwa (S)</td>
<td>Sandy mudstone</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>Ushigakubi (Us)</td>
<td>Massive mudstone</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Kawaguchi (Ks)</td>
<td>Sandstone</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Kawaguchi upper (Ku₂)</td>
<td>Sandy mudstone interbedded with sandstone</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Kawaguchi upper (Ku₁)</td>
<td>Mudstone interbedded with sandstone</td>
<td>3.65</td>
</tr>
<tr>
<td></td>
<td>Kawaguchi lower (KL)</td>
<td>Sandstone interbedded with mudstone</td>
<td>0.33</td>
</tr>
<tr>
<td>Miocene</td>
<td>Araya (A)</td>
<td>Massive mudstone</td>
<td>4.30</td>
</tr>
<tr>
<td></td>
<td>Total area:</td>
<td></td>
<td>14.2 km²</td>
</tr>
</tbody>
</table>

Fig. 7. Landslide areas for each geologic unit in the study region

Yamakoshi and northeast of the earthquake epicenter that represents the area where we focused our efforts to assess the accuracy of landslide observations from satellite imagery. This study region measures approximately 14 km² and represents one of the hardest hit areas in the Uonuma hills (Kieffler et al., 2006). Visual identification of landslides was performed by simply identifying areas where the vegetation was removed due to downslope movement and labeling the full extent of the landslide based on visual interpretation. Visual interpretation was difficult in some instances where the landslide was small or where only part of the slide resulted in lost vegetation. The landslide map developed by the Japan Geographical Survey Institute (GSI, 2004) using traditional aerial reconnaissance was used as the baseline data to which to compare the satellite-based observations. A 1:50,000 geologic map of the Ojiya district (Yanagisawa et al., 1986) was used to correlate the landslides with geologic units. The main geologic units in the study area represent Pleistocene sandstones and mudstones (Table 1).

The satellite images and the GSI landslide map were co-registered to the geologic map to correlate the landslide observations with the geologic units. Co-registration is difficult for satellite images acquired at large off-nadir angles due to the distortion in the imagery, particularly when dealing with mountainous terrain. The co-registration was performed using a Delaunay triangulation warping method, implemented in the image processing software package ENVI (www.rsinc.com), which utilizes user-defined ground control points (GCP) to align the different datasets. However, because of difficulties in identifying a significant number of GCPs (e.g., road intersections) throughout the upland area and because of distortions that vary over short distances (e.g., between valleys and ridges), the accuracy of the co-registration varied significantly across the image. The highlighted region in Fig. 6 represents the area surrounded by the most GCPs, and thus the most accurate co-registration. However, errors in the co-registration due to topographic distortion are still present in this region.

Figure 7 displays the total area of landslides identified by the Quickbird imagery, IKONOS imagery, and the GSI landslide map, as well as the distribution of landslide area between the nine geologic units listed in Table 1. The visual analysis of the Quickbird and IKONOS imagery revealed 1.01 km² and 1.05 km² of landslides, respec-
tively, while the GSI map revealed 1.4 km². Because the visual interpretation of landslides from satellite imagery is based predominantly on the identification of areas with lost vegetation, it is not surprising that the satellite observations underestimate the total area of landslides. Additionally, the GSI map includes smaller landslides that could not be identified in the satellite imagery. Based on the total area of the test region (14.2 km²), the GSI map indicates an overall landslide density (percentage of ground surface, in map view, covered by landslides) of 9.9%, while the Quickbird and IKONOS observations indicate landslide densities of 7.1% and 7.4%, respectively.

In terms of the distribution of landslides by geologic unit (Fig. 7), the satellite observations agree with the GSI map in terms of assigning the largest landslide areas to geologic units Kawaguchi Upper (Ku), Wanazu (W), Shiroiwa (S), and Araya (A). However, these four geologic units represent the units that cover the largest areas in the study region (Table 1); thus landslide density was also computed. Figure 8 plots the landslide density for each geologic unit, as determined by the three datasets. The GSI data in Fig. 8 reveal that the largest landslide densities were experienced in the Pliocene units: Kawaguchi (Ks), Wanazu (W), and Shiroiwa (S). The smallest landslide density was observed in the Araya (A) unit, which is a Miocene massive mudstone.

The landslide densities in Fig. 8 from the satellite observations are generally smaller than those from the GSI map. For some geologic units the underestimation by satellite imagery is greater than 50%, while for others there is good agreement with the GSI map. These differences are affected by the number, area, and size of the landslides within each geologic unit, as well as the direction in which the landslides are facing. The landslide direction impacted the satellite observations because of the large acquisition angles for the imagery. To investigate this effect, twenty-one specific landslides were identified in each data set and their areas compared for different slope directions. Figure 9 displays landslide area ratio, defined as the landslide area identified from satellite imagery divided by the landslide area identified from the GSI map, for west/northwest facing slopes and east/southeast facing slopes. Note that for almost every landslide, the ratio is less than 1.0, indicating a general underestimation of landslide area from the satellite imagery. For the west facing slopes (Fig. 9(a)), the Quickbird imagery significantly underestimates landslide area due to its large acquisition angle from the east. The underestimation is much smaller for the IKONOS imagery because it had a smaller acquisition angle and was pointing from the west. For the east facing slopes (Fig. 9(b)), the IKONOS imagery displays more underestimation than the Quickbird imagery due to its acquisition location from the west. However, the IKONOS underestimation for east facing slopes is generally not as dramatic as the Quickbird underestimation for west facing slopes because of the slightly better acquisition angle for the IKONOS imagery (32° vs. 47°).

In addition to visual analysis, a semi-automated classification algorithm was investigated to assess its potential to locate landslides through the identification of areas with lost vegetation. Initially, a supervised maxi-
imum likelihood classification (Lillesand et al., 2004) was performed in which training data were defined for the different classes in the image (classes included landslides, vegetation, roads, etc.) and these data were used to classify the remaining pixels in the image based on a statistical comparison with the training data for the various classes. However, this analysis resulted in significant confusion between areas of lost vegetation and carp (coil)-raising ponds in the region due to their similar bright signatures in the satellite imagery. Thus, a pairwise classification algorithm was used (Crawford et al., 1999) that considers each class pair separately and uses the characteristics that best distinguish each pair. This pairwise classification analysis resulted in less confusion and identified 0.61 km$^2$ and 0.86 km$^2$ of landslides in the Quickbird and IKONOS imagery, respectively. These values are much smaller than those developed from visual interpretation (1.01 km$^2$ and 1.05 km$^2$ of landslides, respectively), which is not surprising because the semi-automated landslide classification algorithm only considers the areas of lost vegetation, while visual examination allows the trained analyst to interpret the image to define the full landslide geometry. Although semi-automated landslide detection may not produce accurate estimates of the total area of landslides, it could be useful in the future to guide visual interpretation towards areas of significant landslides.

**OBSERVATIONS FROM TERRESTRIAL LIDAR**

During several weeks in November 2004, the two reconnaissance teams visited sites of damaged roadways, structures, and displaced ground and collected LIDAR data from approximately forty individual laser-scan setups. Roadside embankment failures were ubiquitous throughout the mountainous areas. An example of one such embankment failure was shown in Fig. 5, on a steep mountainous section of Highway 252, west of Horinouchi. This two-lane road was built on the northern side of a steeply sloped river-incised canyon and failed toward the south into the bottom of a narrow ravine. Two LIDAR scans were set up on the east and west ends of the failure to minimize the shadow zones. The four frames of Fig. 5 show the processing procedures for producing a surface model: (a) scan the target from multiple perspectives; (b) merge and register the scans; (c) filter out vegetation and render the surface model; and (d) compute deformations on the merged scan points and rendered surface. With this product, a variety of geometric measurements can be made of the ground failure that can be differenced against pre-event topographic survey drawings of the embankment. Hundreds of embankment failures like the Highway 252 failure were observed in the epicentral region.

An example of structural damage recorded by LIDAR is presented in Fig. 10, collected in the damaged portal of the Joetsu railroad tunnel, north of Horinouchi (the north direction is into the tunnel). The portal is founded on a poorly compacted embankment fill that settled during the earthquake and deformed away from the tunnel. The portal pulled away from the tunnel, opening a gap, and settled laterally toward the east (downslope).
Vertical settlement was more pronounced on one side of the portal causing it to undergo a minor rotation. A photograph of the embankment and tunnel damage is presented in Fig. 10(a), looking north. In the interior of the tunnel, displacement of the portal was observed in the walls and ceiling. An oblique view of the LIDAR point-cloud data can be seen in Fig. 10(b). Here, the portal (front section) and tunnel are viewed from above and south of the portal entrance. The left-lateral offset of the portal relative to the tunnel is clearly visible in the LIDAR model. In the LIDAR imagery, precise centimeter-scale measurements can be made of the three-dimensional deformation of the structure. The tunnel suffered 36 cm of separation and 21 cm of left-lateral displacement of the portal as measured by the LIDAR imagery. Displacement of the portal and failure of the gravel embankment also resulted in deformation of the railway tracks, clearly visible in the LIDAR scans. LIDAR 3-D imaging software was used to rotate the data into map view looking down from above through the roof of the portal (Fig. 10(c)). In this view, the portal separation and left-lateral displacement of the portal relative to the tunnel can be clearly seen in the tunnel wall. The data-hole in the center is the non-illuminated area beneath the tripod.

The natural slope failure of the Shiroiwa (White Rock) landslide dislodged rock debris along a steep unbuttressed cliff corner on the banks of the Shinano River, along former Highway 17 at Myoken, Nagaoka City (Fig. 11(a)). This large rockslide occurred in the Shiroiwa (S) formation and dislodged an entire cliff-face of soft and friable weathered mudstone with laminated sand. It killed several people driving on this portion of the highway. The rock slope, a portion of the highway cutand-fill, and five vehicles were swept into the Shinano River in a catastrophic collapse of the bluff. The roadbed on the north side of the slide collapsed into the river, while on the south side of the landslide block debris completely covered the roadbed just north of the highway bridge. Eight total LIDAR scans were taken on the north, western, and southern sides of the slide to characterize the volume, runout, and morphology of the slide. The point cloud obtained of the south side of the landslide is shown in Fig. 11(b). Based on these data, the height of the cliff at Shiroiwa was approximately 35 meters above the Shinano River and the run out distance averaged 130 meters. The road bed at the southern end of Route 17 just north of the bridge was completely covered with debris. That portion of the road bed was 13 meters above the Shinano River toward the base of the slope, well down slope from the crest of the cliff that released the rock avalanche. A number of the largest intact boulders in the avalanche were in excess of 6 meters to a side, as measured in the LIDAR data. The embankment fill on the south side of the landslide settled during the event and the LIDAR data shows an average of 21 cm of compaction, visible as a step off the bridge (Fig. 11(b)).

A LIDAR survey was conducted of one of the two Yokowatashi translational rock slides along Highway 291 just south of the Shiroiwa (White Rock) landslide shown in Fig. 11. Figure 12(a) is an aerial photograph of the two rockslides. Both occurred in the Shiroiwa (S) formation along bedding planes on dip slopes dipping about 25° to the west (downdip). The LIDAR survey was conducted on the northern (left) rockslide by Dr. Robert Pack (Utah State University) using an older Reigl LIDAR instrument (Kayen et al., 2006). The shear surface of this particular block slide is planar and occurred along sandstone bedding planes in the dip-slope orientation. It is this dip-slope geometry along Highway 291 that likely led to the multiple failures in the area and subsequent burial of this section of highway.

A contour map of the rockslide was produced from the LIDAR data by processing the raw data into a digital elevation model using ESRI ArcGIS mapping software (Fig. 12(b)). The horizontal shading represents elevation bands sliced into 1 meter intervals. LIDAR data revealed the asymmetry of the side scarp due to the orientation of the rock bedding plane relative to the ground surface. The scarp is approximately 5 meters high on the left
Fig. 12. (a) Aerial photograph of Yokowataishi rockslides along Highway 291 (from ORIS http://www.oris.co.jp/jishin2004/ h16jishin.htm) and (b) Contour map of the rockslide derived from the LIDAR survey (from R. Puck, Utah State University): The head of the slide is at the bottom of the figure: A side lateral scarp of 5 meters is on the south (left) side, but is not present on the north side: Slide debris is located at the toe of the feature (37.3313N, 138.8270E).

(south) flank of the slide and has virtually no relief on the right (north) flank of the slide. The contour map also shows the planar slide surface controlled by bedding. The trees found on the lower elevation part of the contour map (at the top of Fig. 12(b)) were transported upright as they slid downslope on the translating block of rock. The rockslide is approximately 70 meters long and 40 meters wide. The relatively uniform slope angle is 24.6°, which is similar to the bedding angle of 30° indicated for the slope on a geologic map of the area (Yanagisawa et al., 1986).

SYNTHESIS OF SATELLITE AND FIELD OBSERVATIONS

One benefit of obtaining satellite imagery soon after an earthquake is the ability to capture the extent of damage shortly after the event, often before technical reconnaissance teams can reach the affected area. Additionally, because satellite imagery covers a large area, it allows one to consider fully the context of a failure and potential interactions between failures. These observations are difficult to formulate from the ground during traditional reconnaissance and can complement field reconnaissance and field LIDAR observations.

Figure 13 is a satellite image of the area surrounding the Shiroiwa (White Rock) landslide acquired the day after the earthquake. This image allows one to consider how the Shiroiwa landslide and other failures in this region interacted to cause the damage observed in the field. Figure 13 indicates that the Shiroiwa landslide blocked the outflow of two creeks that flow into the Shinano River; one flowing from the east through Uragara village, and the other flowing north through a channel that lies at the base of the hills. The first creek runs south of Uragara village but mud and debris (bright areas) can be observed between buildings throughout the village, indicating that the creek overflowed its banks with landslide debris that originated upstream. During field reconnaissance, this area was not easily accessed so it was not possible to determine the source of the debris while in the field. The second creek was blocked by the rock slides shown in Fig. 12, and this blockage caused this creek to overflow its banks and deposit water and landslide debris (bright area west of block slides) over an area of approximately 100,000 m². The damage in this area was exacerbated by the blockage from the Shiroiwa landslide because water and landslide debris could not drain into the Shinano River. During field reconnaissance (17-20 November), the flooded area in Fig. 13 had already been drained, the channelized creek was almost repaired, and the highway at the base of the block slides was being repaved, such that it was impossible to understand fully the damage caused by the block slides. Thus, the satellite imagery revealed earthquake effects that could not be fully understood while in the field.

CONCLUSIONS

Remote sensing via high-resolution satellite imagery and LIDAR scanning can provide important observations of earthquake effects that supplement traditional observations from field reconnaissance. This paper discussed the basic concepts regarding satellite imagery and LIDAR scanning for earthquake reconnaissance and provided remote sensing-based observations of earthquake damage from the 2004 Niigata Ken Chuetsu earthquake.

The large number of landslides was one of the most significant effects of the Niigata Ken Chuetsu earthquake. These landslides occurred predominantly in the Uonuma hills around Yamakoshi. High-resolution (1 m or less) Quickbird and IKONOS satellite images were acquired the day after the earthquake and used to document the locations of landslides throughout the most heavily
damaged areas. Although the satellite images were collected at very adverse acquisition angles, which resulted in image distortion, the satellite data could still be used to document the spatial distribution of landslides. In comparison with a landslide map developed by traditional aerial reconnaissance, the satellite observations for this earthquake underestimated the landslide area by about 25%. This underestimation was caused by the inability to discriminate smaller landslides in the satellite imagery, difficulties in visual identification of landslides in the distorted topography, and the fact that the sides of slopes facing away from the satellites were de-emphasized, or even hidden, due to the large acquisition angles. Images acquired at more favorable acquisition angles would not have been affected as severely by distortion. Nonetheless, the satellite observations generally agreed with the observations from aerial reconnaissance in terms of identifying the geologic units with the largest landslide density.

LIDAR was used during field reconnaissance to collect three-dimensional data of several landslide and ground failure sites. These data provided detailed information regarding the morphology of these failures and allowed for precise measurement of deformations, geometries, and the effects on structures (tunnels, bridges). LIDAR imagery of the Joetsu Railroad tunnel portal at Horinouchi revealed 36 cm of separation and 21 cm of lateral displacement, while the LIDAR imagery of the Shiroiwa (White Rock) landslide at Myoken indicated a runout distance of about 130 meters. The Yokowatashi block slides on Highway 291 were also imaged with LIDAR and these data were used to measure the failure area and the slope of the shear surface.

Satellite imagery and LIDAR scanning were used successfully during and after the reconnaissance of the Niigata Ken Chuetsu earthquake to document the effects of the earthquake. These remote sensing technologies provided information at different scales (sub-centimeter to kilometer levels) that, when combined with traditional field observations, allowed for a more comprehensive assessment of the damage caused by this earthquake. In the future, satellite imagery and LIDAR, as well as other remote sensing technologies, will play an increasing role in documenting and understanding the effects of earthquakes.

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