Western Coastal and Marine Geology

Terrestrial LIDAR Investigation of the December 2003 and January 2007 Activations of the Northridge Bluff Landslide, Daly City, California

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Datum Information

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) and projected to Universal Transverse Mercator, Zone 10N coordinates.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this report, refers to distance above the vertical datum.

Metadata for the products described in this report are available at: *http://walrus.wr.usgs.gov/infobank/l/ld104ca/html/l-d1-04-ca.meta.html* and *http://walrus.wr.usgs.gov/infobank/l/l107ca/html/l-1-07-ca.meta.html*

Terrestrial LIDAR Investigation of the December 2003 and January 2007 Activations of the Northridge Bluff Landslide, Daly City, California

By Brian D. Collins, Robert Kayen, Thomas Reiss, and Nicholas Sitar

Introduction

On December 20, 2003 and again on January 1, 2007, landslides occurred along the coastal bluff that forms the west boundary of Daly City, California sending debris as far as 290 meters downhill and 90 meters into the ocean. This area is known for large landslide events where 150-meter tall coastal bluffs extend southward along the west boundary of San Francisco and San Mateo Counties (Fig. 1). The 2003 and 2007 landslide events occurred west of Northridge Drive in Daly City and just south of Avalon Canyon, which bisects the bluffs in this area (Fig. 2). Residential development, utility lines and roads occupy the land immediately east of this location. As part of a comprehensive project to investigate the failure mechanisms of coastal bluff landslides in weakly lithified sediments along the west coast of the United States, members of the U.S. Geologic Survey (USGS) Coastal and Marine Geology (CMG) Program performed reconnaissance mapping of these landslide events including collection of high-resolution topographic data using CMG's terrestrial LIDAR laser scanning system.

This report provides a brief background on each landslide event and presents topographic datasets collected following each event. Downloadable contour data, images, and FGDC-compliant metadata of the surfaces generated from the LIDAR data are also provided. LIDAR data collection and processing techniques used to generate the datasets are outlined. Geometric and volumetric measurements are also presented along with high-resolution cross-sections through various areas of the slide masses and discussion concerning the slides present (2007) configuration is provided.

Figure 1. Location map of Northridge Bluff Landslide, Daly City, California (Photo courtesy Cotton, Shires, and Associates)

Figure 2. Site map of Northridge Bluff Landslide, Daly City, California showing key features

Geologic and Regional Background

The Northridge Bluff Landslide is located on the Pacific Ocean coastline in Daly City, just south of the city and county border with San Francisco, California (Fig. 1). The landslide is located in an area of steep bluffs that extend from sea level up to approximately 150 meters in elevation. The bluffs are composed of weakly consolidated sediments of the Merced Formation (approximately 0.5 to 3.0 ma), consisting of steeply dipping (~65°) sandstones and siltstones (Clifton and Hunter, 1999). A comparatively thin layer of artificial fill about 5 meters thick overlies the Merced Formation units at the top of the landslide area (GEI, 1998).

The landslide is located in the vicinity of type section "B" of the Merced Formation, as mapped by Clifton and Hunter (1987, 1999); the Merced is composed of sediments deposited over a full transgressive-regressive sea-level sequence. Units composed of silt are indicative of marine deposition, while those composed of sands and gravelly units are indicative of terrestrial deposition. Sediment mineralogical provenance dating by Hall (1965) and tephrachonologic dating by Sarna-Wojcicki and others (1985) show that the type B sequence was deposited at least 650 ka from locally derived sediments of the nearby Coast Ranges, prior to outflow of Sierra Nevada-born sediments through the Golden Gate to the north (Clifton and Hunter, 1999; Anderson and others, 2001).

Following deposition, Merced Formation units were tilted and uplifted, although folding seems to predate any tectonic movement caused by the nearby San Andreas Fault system (Clifton and Hunter, 1999). The strike of stratification consistently trends northwest (N 60 to 65 W) with a northward dip of 60 to 85 degrees (Cotton, Shires, and Associates, 2004b). The bedding orientation thus faces in-slope to the trend of the bluff face and coastline (N5W) in this area. Tectonic forces have further led to the creation of extensive fracture networks within the bedrock. These fracture networks have been linked directly to the instability of the Northridge Bluff Landslide (Cotton, Shires, and Associates, 2004b).

Landsliding has been documented in this area for over 100 years. In the early 1900's the Ocean Shore Railway ran along an alignment still visible at the mid-height of these bluffs. The Railway experienced severe damage from landsliding, in particular as a result of the 1906 San Francisco earthquake. The California Department of Highways assumed responsibility of the grade in the 1930's for the location of California State Highway 1 but also responded to constant landsliding of the road bed until the Department abandoned the right of way following major failures in the 1957 Daly City earthquake (Sloan, 2005). These earthquake-induced landslides are described in Lawson (1908) and Bonilla (1959). Landslides on the Daly City bluffs also occurred during the 1989 Loma Prieta earthquake (Plant and Griggs, 1990; Sitar, 1990). However, whereas these earthquakes caused severe landsliding of these bluffs, winter storm events are the most frequent cause of failures, with reports made regularly in most years and especially during the past two large El Niño events to affect northern California in 1982-83 (Lajoie and Mathieson, 1998) and in 1997-87 (Jayko and others, 1999). The 2003 and 2007 Northridge Bluff Landslide events carry on the trend of storm-induced failures in the area.

Landslide History

Landsliding in the Northridge Bluff area extends some 10 years to the 1997/1998 winter season. Engineering consultant reports (Cotton, Shires, and Associates, 2004a,b; GEI Consultants, 1998), government investigations (Jayko and others, 1999), and news media reports (Pimentel and others, 1998) provide descriptions of various events during this time period, and along with site specific observations made since 2003, were used to reconstruct the landslide history of the area.

On December 20, 2003, part of a steep coastal bluff failed as a complex landslide mass along the cliffs that form the west boundary of Daly City, California (Fig. 3). The main slide mass measured approximately 290 meters in length, 120 meters in width, and 12 meters in depth; the volume of landslide material was estimated to be between 305,800 and 382,300 cubic meters. The failure spanned

Figure 3. The December 20, 2003 Northridge Bluff Landslide Event (Photo from Cotton, Shires, and Associates, 2004b)

the full 140 meter height of the bluff and deposited debris as far as 90 meters into the ocean (Fig. 4). Wave action rapidly removed the toe debris following failure and steepened the overall slope profile. Part of the slope within the initial slide mass then failed on February 21, 2005; however, this failure was minor compared to the volume of the initial event. On January 1, 2007, the slope failed again, mobilizing a minimum estimate of 120,800 cubic meters of material from the existing landslide area (Fig. 5). This landslide measured roughly 260 meters in length, 80 meters in width, and a minimum 8 meters in depth. Debris was deposited 40 meters into the surf zone and was eroded by wave action within a few weeks of the event.

Oblique aerial photographs from 1972, 1979, and 1987 (California Coastal Records Project, 2007) indicate that even though this area showed signs of general landslide complexes no signs of a

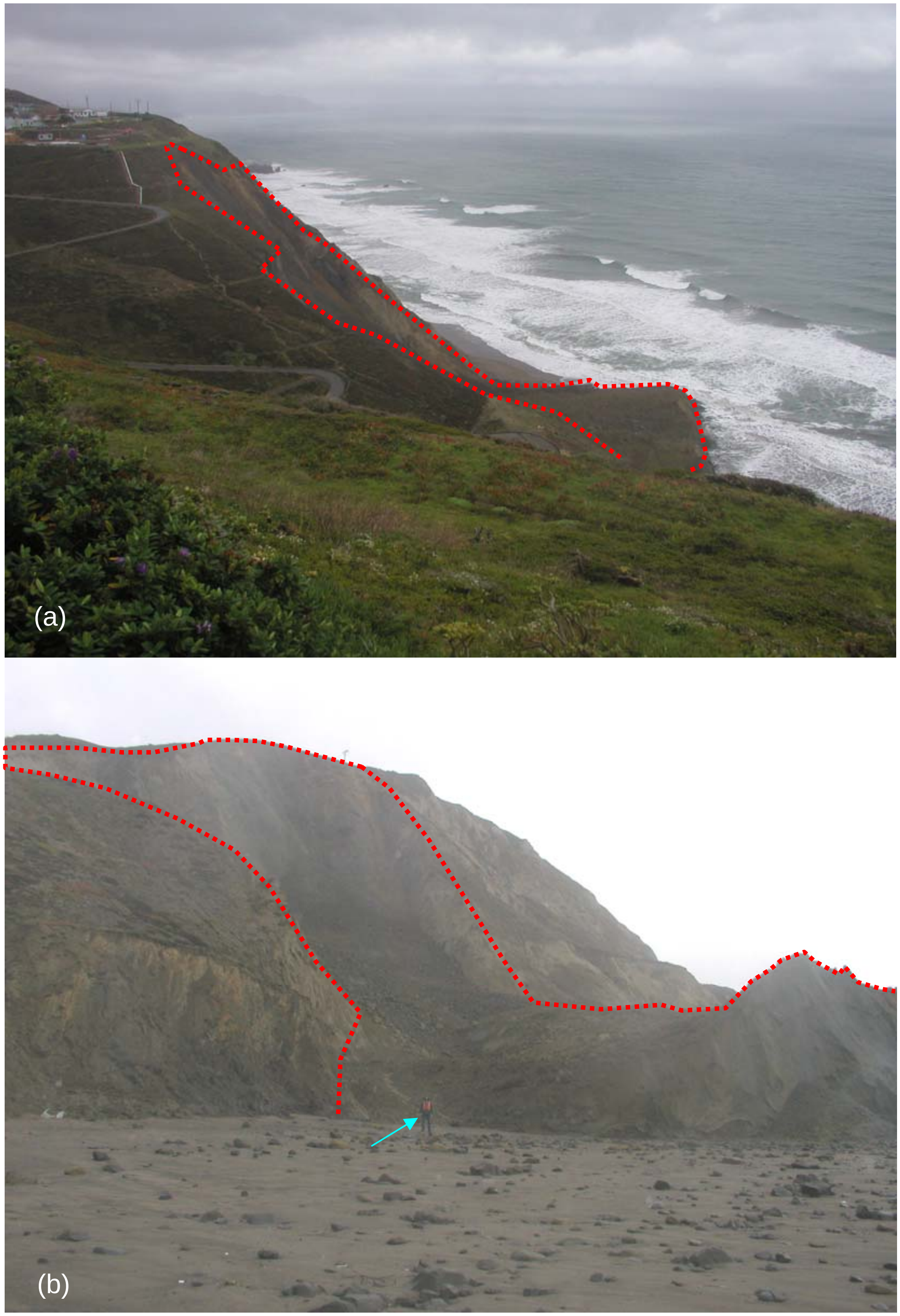

Figure 4. Lateral (a) and beach (b) views and lateral extents of the December 20, 2003 Northridge Bluff Landslide Event. Arrow points to field assistant on beach for scale.

Figure 5. The January 1, 2007 Northridge Bluff Landslide Event. Bluff height is about 140 meters.

critically unstable condition, including a lack of any defined head scarp or toe movement, existed during this time. Landsliding in the Northridge Bluff area was first reported in April 1998 during field reconnaissance efforts for repair to a failed storm drain located immediately to the north along the axis of Avalon Canyon (Fig. 2). The storm drain failed in February 1998 and caused severe landsliding in and along the east and south walls of the canyon. Reports note that landslide initiation and movement in the nearby Northridge Bluff Landslide area was occurring due to toe erosion from wave attack at this time and that head scarp advancement threatened the western property boundary of a church located at the top of the slope (Fig. 2). In early May 1998, several weeks later, tension crack formation in the parking lot adjoining the church was observed. Repairs associated with the failed storm drain in Avalon Canyon involved the removal of the church structure along with 306,000 cubic meters of earth materials from the top of the slope as a source for construction fill and to potentially assist with stabilization of the now formed Northridge Bluff Landslide.

The landslide area continued to evolve and according to aerial photo analysis of the area the boundaries of the main landslide scarp, lateral limits, and presence of toe debris were all fully formed by August 2000. Oblique aerial photo analysis performed as a part of this report shows that wave action caused continuous changes to the landslide toe area until the massive failure on December 20, 2003.

Construction of a new church building at the top of slope, first initiated in 2000, was only minimally interrupted following the landslide at that time.

The December 2003 landslide occurred primarily along the existing scarp boundaries, present at least as far back as 2002. However, during the 2003 landslide, the head scarp also propagated approximately 40 meters upslope. Within a few weeks of the failure, wave action rapidly cut the slope toe back in line with neighboring bluff areas to the north and south. Additional erosion of the head scarp area and toe debris continued through the 2004-05 winter including a reactivation of the landslide on February 21, 2005. On January 1, 2007, failure occurred again, mobilizing material along the entire length of the existing landslide scar and widening and deepening the head scarp area.

Methodology – Terrestrial LIDAR Laser Scanning

The terrestrial LIDAR technique (3D laser scanning) consists of sending and receiving laser pulses to build a point file of three-dimensional coordinates of virtually any surface. The time of travel for a single pulse reflection is measured along a known trajectory such that the distance from the laser, and consequently the exact location of a point of interest, is computed. Using this methodology, data collection commonly occurs at rates up to 12,000 points per second generating a "point cloud" of three-dimensional coordinates. Acquisition of sufficiently dense point clouds can fully describe site topography. The point files generated from data collection are typically transformed into three-dimensional surfaces for cross-section and volumetric analyses. This technology has been used to study the evolution of coastal bluffs in Pacifica, California, located just south of Daly City, since 2002 (Collins and Sitar, 2002, 2004, 2005).

In this study, the CMG's Riegl Z210 laser scanner (Riegl, 2007) was utilized as a tripod mounted survey instrument (Fig. 6) and transported by backpack to each scanning location. Multiple scans were collected during each survey to fill in "shadow zones" of locations not directly in the line of

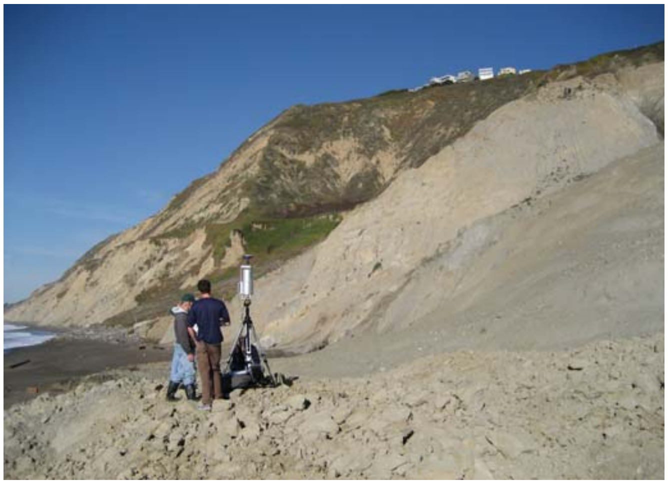

Figure 6. The USGS Coastal and Marine Geology program's terrestrial LIDAR unit at the Northridge Bluff Landslide. Close-up shows laser and GPS antenna used for georeferencing instrument location.

sight of the laser and to expand the range and density of the point data. Data were collected at a rate of 8000 points per second, scanning a range of 336 degrees in the horizontal direction and plus and minus 40 degrees from the horizontal in the vertical direction. Georeferenced coordinates of the scan locations were determined by either locating the instrument over known survey benchmarks or by collecting GPS data via an antenna mounted directly to the laser.

Processing of the data was performed using I-SiTE software (I-SiTE, 2007) specifically designed to handle laser scan data. Details of the processing procedures used for each landslide event are provided in the following sections of this report. Metadata for the data collection effort and data products are available at *http://walrus.wr.usgs.gov/infobank/l/ld104ca/html/l-d1-04-ca.meta.html* and *http://walrus.wr.usgs.gov/infobank/l/l107ca/html/l-1-07-ca.meta.html* (U.S Geological Survey, 2007).

Data Collection

LIDAR data collection of the December 20, 2003 landslide event took place on January 6, 2004, about two weeks after the failure. Five scans were collected of the slide area: one from a vantage point on the immediate north side of the slide, and four from locations along the beach and toe area of the slide debris (Fig. 7). Two scans were performed at a higher point density (approximately 1.1 million points each) to capture features of the landslide scarp, whereas three scans were performed at a lower point density (approximately 0.4 million points each) to capture peripheral details, including the landslide debris run-out zone. One scan (AC01-2004) was located over a survey control point (STA-B) and backsighted to an additional survey control point (STA-C) previously installed by Daly City's consultants. These points were utilized for georeferencing purposes.

Data collection of the January 1, 2007 event took place on January 9, 2007, about one week after the failure. Six scans were collected of the landslide: two from vantage points at the top and north mid-section of the slide, and four from locations along the beach and toe area of the slide debris (Fig. 8). All points were collected at a high point density (approximately 1.2 million points each). Survey control for each scan was obtained by utilizing a pair of continuously operating Ashtech, Z-Xtreme, geodetic-quality, dual-frequency (L1/L2) GPS receivers (Ashtech, 2007). One receiver was mounted to the scanner while the second acted as a fixed, temporary base station located within 300m of each scanner position. Data collected by the base receiver was post-processed by the National Geodetic Survey's OPUS (Online Positioning User Service) to obtain a geodetic position (NGS, 2007a). Data collected by the "roving" receiver attached to the scanner was processed differentially against the base station data using Ashtech's proprietary software in a Stop-and-Go methodology.

Data Filtering

Point data from each set of scans was subjected to a series of filters to remove non-ground surface and extraneous laser returns from the point clouds. Due to the close proximity of the scan location to the near-shore zone, a considerable amount of data was obtained of water and wave surfaces.

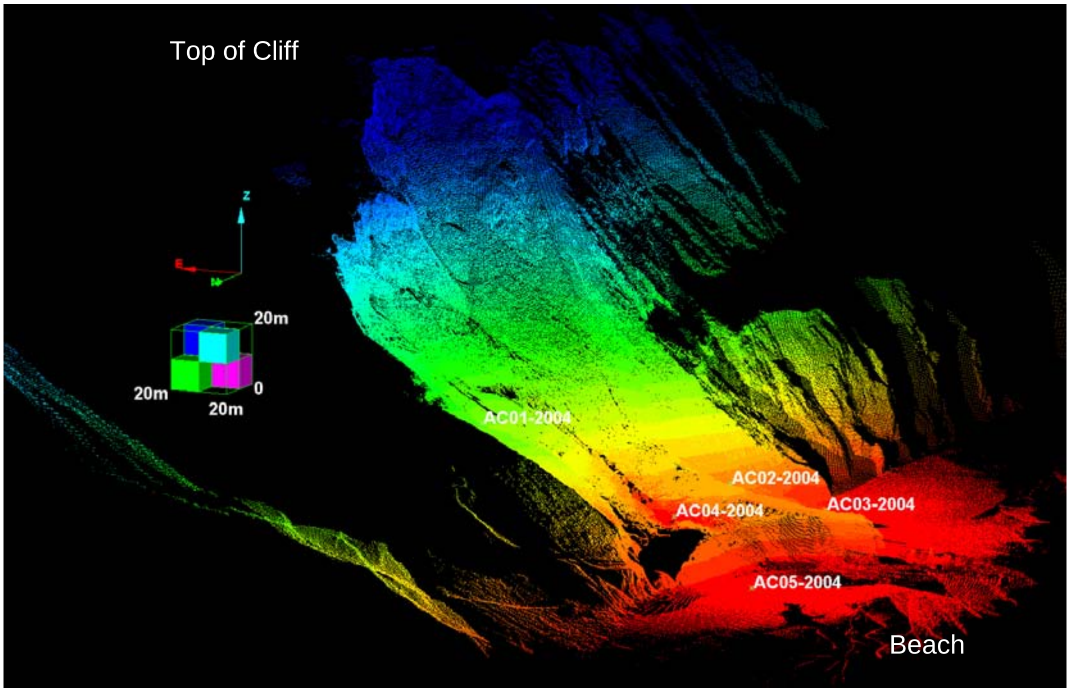

Figure 7. LIDAR setup locations and data coverage for the 2003 landslide event. Color intensity scale is used only to show relative elevation.

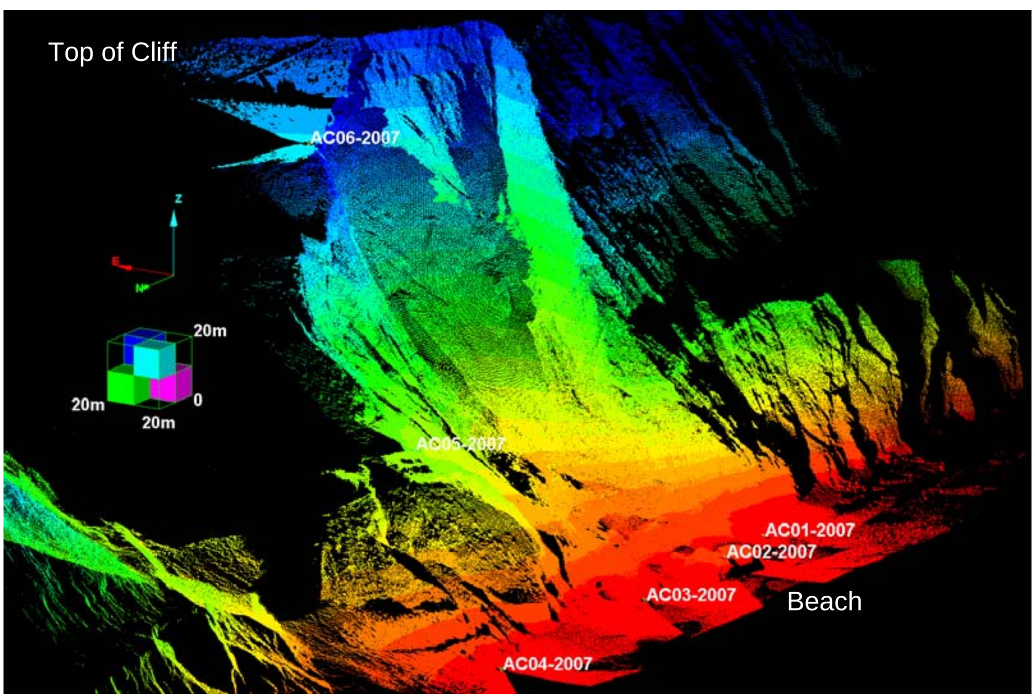

Figure 8. LIDAR setup locations and data coverage for the 2007 landslide event. Color intensity scale is used only to show relative elevation.

Points reflected from the ocean surface were therefore cropped from each of the point clouds. Next, an isolated point filter was used to remove single point instances occurring above the land surface. These isolated points are usually a result of reflections from moisture in the atmosphere. Topographic filters that select the lowest point in the point clouds, typically used to remove vegetation from point clouds, were not utilized for this data set because the majority of the point data represented the surfaces of interest, e.g. the landslide scarp and debris surfaces. Finally, for generating topographic surfaces of the landslide areas, a 20 centimeter minimum separation filter was applied to construct a data set with a less dense network of points. This provided a point data set that enabled more rapid surface rendering.

Data Registration and Georeferencing

The bulk of LIDAR data processing occurs when the individual scan data sets are merged to form a single model of the area of interest, termed the registration process. Georeferencing is performed when the scans are assigned geographic coordinates consistent with a pre-selected datum and projection. If the geographic locations of one or more of the scan origins are known, these steps can be performed concurrently. In the December 2003 event data set, geographic coordinates for a single scan (AC01-2004) were known. All other scans were sequentially registered to this single scan using direct translation and rotation of the data to form a best fit with their neighboring scans. In the January 2007 event data set, geographic coordinates for all scanner locations were known via GPS surveying. All scans were registered by rotating each additional scan about its origin to obtain a best fit of the data to neighboring scans. Because the origin of each scan position was known and considered fixed, translation of scans was not allowed.

The registration process of the raw point data was performed by a surface registration algorithm using a best fit between the topography defined by points in neighboring scans. Because the surface registration technique relies on "rough" topography (defined as jagged, non-flat edges and objects), all available data points were used from each scan file. Typical registration error using this method was 25 to 30 cm, that is, each point is within this range of a point describing similar features in a neighboring scan. In some cases, the registration fit was increased by modeling each scan as a surface. Registration between scans was recalculated using the best fit between each scan and the surface triangulation of its neighboring scan resulting in a decreased average registration error of 10 cm.

Surface Generation

The final product of LIDAR data processing is the generation of three-dimensional surface models. Here, these models represent the topographic surface of each landslide area following each event and were created through a series of steps. After filtering (see above), a surface was generated from each scan file using a spherical surface algorithm (I-SiTE, 2007). Because spherical triangles typically model near-vertical to vertical point data better than linear triangles, this algorithm is better suited for the steep topography present in the Northridge Bluff Landslide datasets when compared to typical topographic triangulation algorithms. A best fit of all spherical surfaces was generated by resampling each spherical surface on a 0.3 meter grid to create the final topographic surface for each data set. To create a more realistic estimate of the pre-2007 event geometry, the December 2003 event surface was modified at the toe area to account for the extensive toe erosion that occurred between December 2003 and January 2007 (Fig. 9). The debris that extended onto the beach was manually removed from the surface and a steep slope was constructed to join the flat beach surface with the 2003 landslide surface. While this reconstruction was one of many possible modifications that could have been performed to achieve a more realistic pre-2007 event surface, this change was the most well constrained by field observations and photo interpretations. Other changes, such as modifications from surface water erosion and gullying of the landslide debris

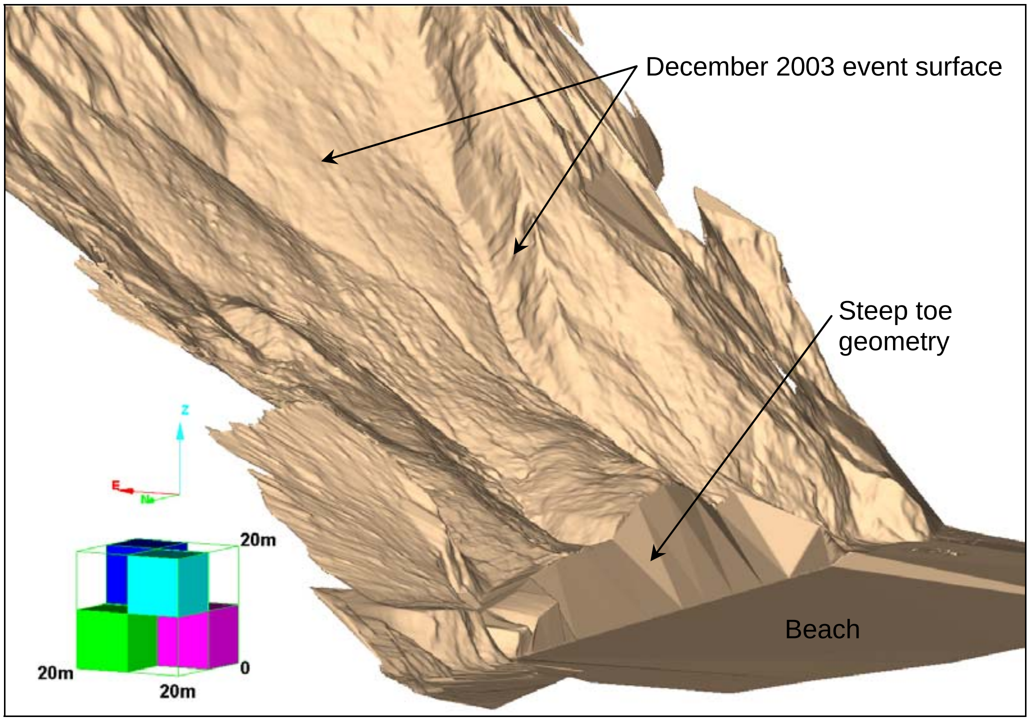

Figure 9. Topographic surface showing construction of pre-2007 landslide event toe geometry.

were not known to sufficient detail to recreate their geometry. Each of these completed surfaces was used to perform geomorphologic cross-sections analysis and volumetric change calculations.

Results

Results from the two terrestrial LIDAR surveys of the Northridge Bluff Landslide consist of survey control data, raw and processed point data, and final surface models, cross-sections, and volumetric measurements.

Survey Control

Control and backsight survey points collected by total station survey and used for registration of the December 2003 event data set were initially provided in California State Plane coordinates, referenced to the North American Datum of 1983 (NAD83) and the National Geodetic Vertical Datum of 1929 (NGVD29). Coordinates were transformed to Universal Transverse Mercator projection coordinates, referenced to NAD83 and the North American Vertical Datum of 1988 (NAVD88) through a series of coordinate transformations using the National Geodetic Survey's Geodetic Toolkit (NGS, 2007b). Coordinates for the single known control point (STA-B) and the associated back-sight point (STA-C) for both projections are provided in Table 1. Control point error for these coordinates are estimated to be less than 2 cm based on typical maximum errors associated with total station surveys.

Table 1. Survey Control for Northridge Bluff Landslide – December 2003

California State Plane Coordinates (NAD83, CA SP Zone0403, US Survey Feet, NGVD29, Feet)					
Control Point	**Northing (ft)**	**Easting (ft)**	**Ground Elev. (ft)**	**Instrument Height (ft)**	**Instrument Elev. (ft)**
STA-B (AC01-2004)	2077005.8930	633072.6623	156.504	2.998	159.502
STA-C	2077011.2367	5984242.1784	N/A	N/A	N/A
Universal Transverse Mercator Coordinates (NAD83, UTM Zone10N, Metric, NAVD88, Metric)					
Control Point	**Northing (m)**	**Easting (m)**	**Ground Elev. (m)**	**Instrument Height (m)**	**Instrument Elev. (m)**
STA-B (AC01-2004)	4170670.359	544502.251	48.544	0.914	49.458
STA-C	4170671.467	544482.783	N/A	N/A	N/A

Table 2. Survey Control for Northridge Bluff Landslide – January 2007

Universal Transverse Mercator Coordinates (NAD83, UTM Zone10N, Metric, NAVD88, Metric)					
Control Point	**Northing (m)**	**Easting (m)**	**Ground Elev. (m)**	**Instrument Height (m)**	**Instrument Elev. (m)**
AC01-2007	4170565.103	544433.748	4.225	1.610	5.835
AC02-2007	4170605.648	544423.311	7.678	1.716	9.394
AC03-2007	4170655.558	544423.118	4.570	1.650	6.220
AC04-2007	4170753.436	544417.118	4.447	1.676	6.123
AC05-2007	4170672.316	544501.441	48.290	1.562	49.852
AC06-2007	4170577.924	544601.503	116.186	1.830	118.016

Control points used for registration of the January 2007 data set were collected in NAD83 (CORS96) and NAVD88 geodetic positions and projected directly to UTM coordinates. Processed survey coordinates for each scanner location of this survey are provided in Table 2. Combined horizontal and vertical control point error for these coordinates averages 3 cm.

Point and Surface Data

The LIDAR data for each landslide event consists of several million points, each describing a three-dimensional coordinate of a point on the ground surface. The full data point cloud for the 2003 event and 2007 event are shown in Figures 7 and 8. A detailed view of a single point cloud (Fig. 10) shows the complexity of the point data, including plainly visible features such as the head scarp and beach area. The non-laser points (termed "sky-points"), collected by the laser's integrated color sensor, may be used to view the topographic data in relation to its setting for a more realistic perspective (Fig. 11).

Three surfaces were constructed from the two landslide data sets: a December 2003 post-event surface, a post-December 2003 but pre-2007 event surface with an assumed steep toe geometry and a January 2007 post-event surface. As discussed, the pre-2007 event surface was constructed to account for several years of wave action that removed landslide debris, located at the toe and beach, previously deposited from the 2003 event. The surface consists of the 2003 post-event surface fused with a toe geometry that blends in with existing cliff profiles immediately north and south of the landslide area.

The final surface for the December 2003 event consists of 712,000 points modeled by 1.4 million triangular facets describing an area 54,600 m^2 in size (Fig. 12). The final surface for the pre-2007 event consists of 682,000 points modeled by 1.4 million triangular facets describing an area 51,300 m^2 in size (Fig. 13). The final surface for the January 2007 event consists of 778,000 points modeled by 1.5 million triangular facets describing an area 57,900 m^2 in size (Fig. 14). Each of these

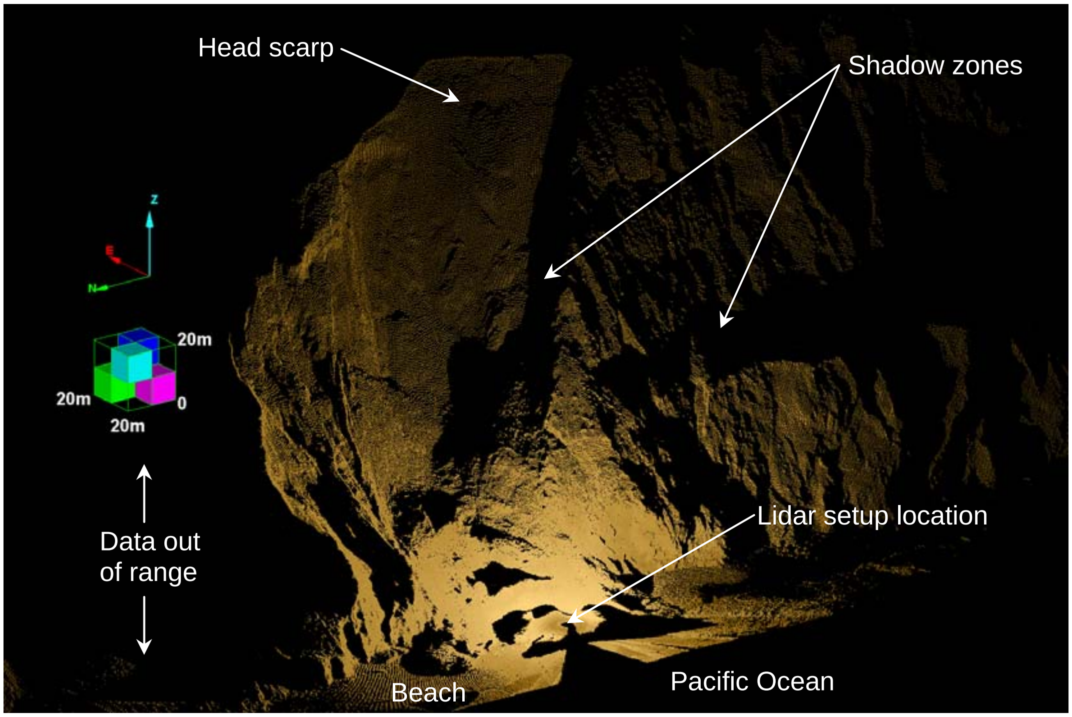

Figure 10. Typical point cloud data from a single scan of the Northridge Bluff Landslide following the January 1, 2007 event. Black areas indicates shadow zones, filtered data (ocean) and areas where no data were collected beyond the range of the laser.

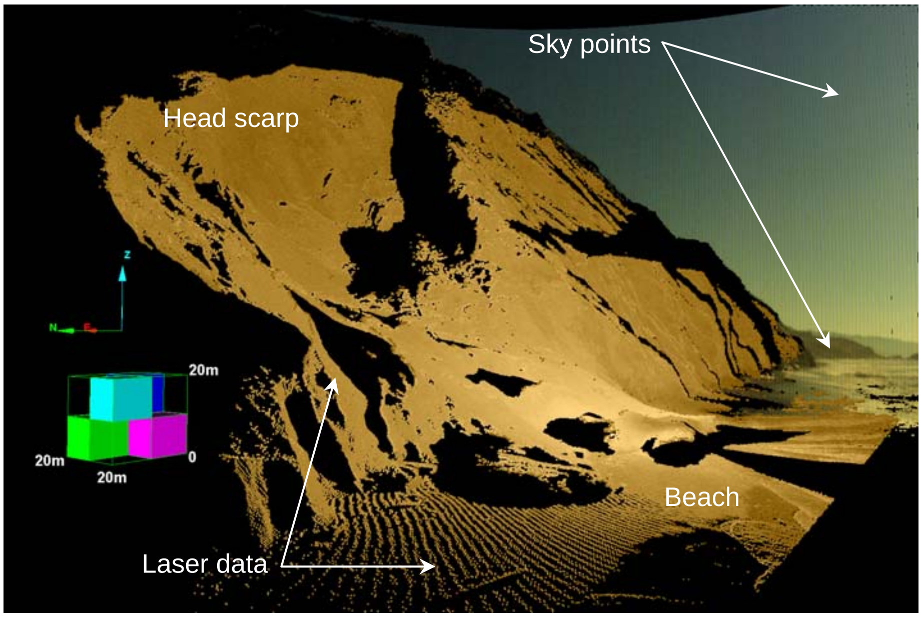

Figure 11. Point cloud showing laser data and “sky points” of background (non-laser) data collected via laser-integrated color sensor.

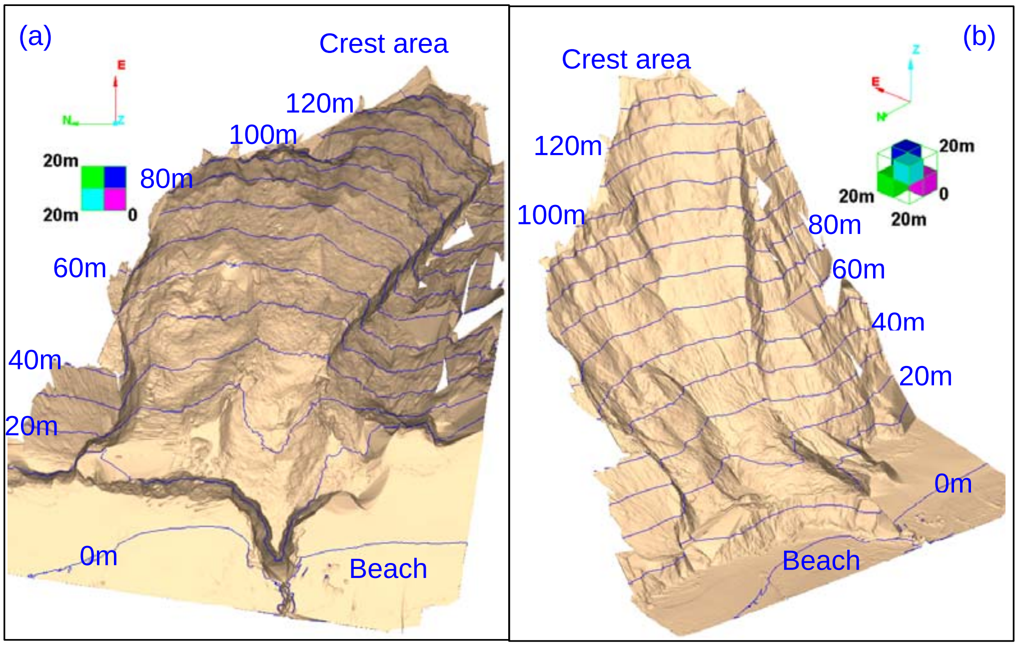

Figure 12. Plan (a) and oblique (b) surface views of the December 2003 event with 10-meter contour intervals. Holes (white areas) represent areas where no data were collected.

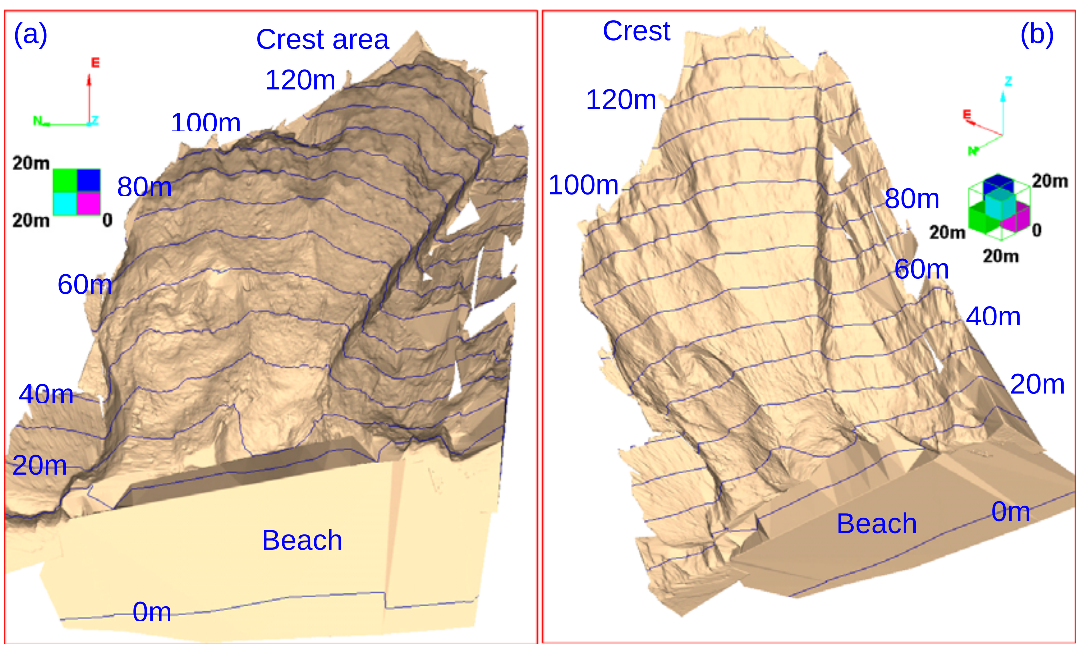

Figure 13. Plan (a) and oblique (b) surface views of the post-December 2003 event but pre-2007 event constructed surface with 10-meter contour intervals. Holes (white areas) represent areas where no data were collected.

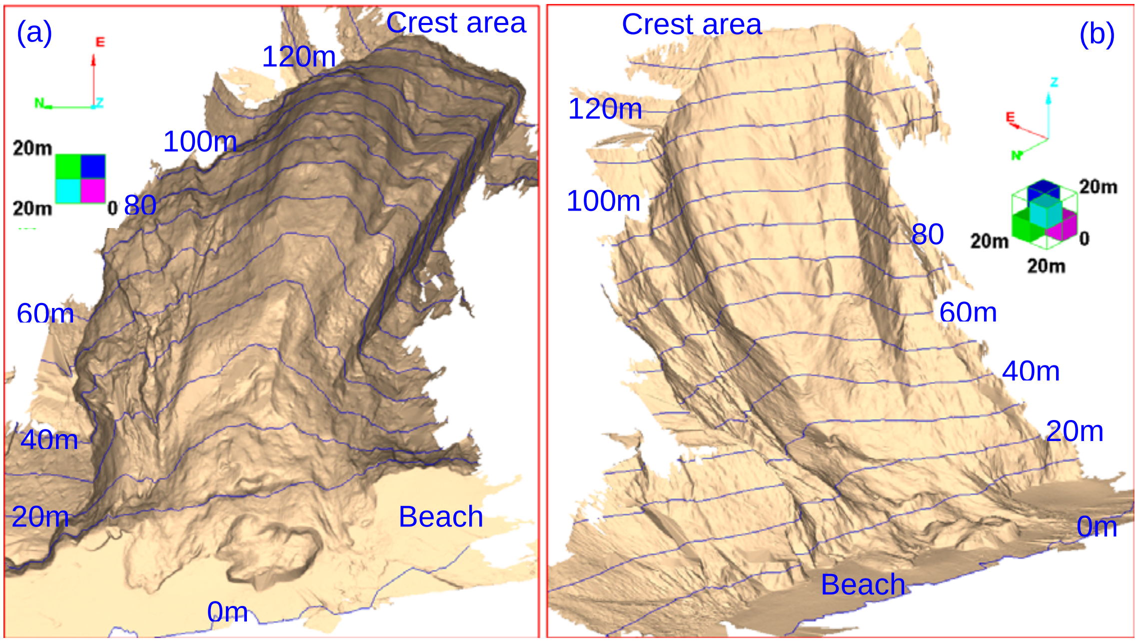

Figure 14. Plan (a) and oblique (b) surface views of the January 2007 event with 10-meter contour intervals. Holes (white areas) represent areas where no data were collected.

surfaces represent the estimated topography (horizontal and vertical coordinates) to within 15 cm of the true surface at the referenced point in time, with the exception of the toe area for the pre-2007 surface, which represents an assumed toe profile and thus less exact geometry.

Data coverages, available as topographic maps with 1-meter contour intervals (Fig. 15), are accessible through digital download for each surface. Contour data in XYZ format (.txt), AutoCAD Drawing Interchange format (.dxf), and associated FGDC-compliant metadata for each file are available through the links provided in Table 3. Data files are compressed using WinZip 9.0 (WinZip, 2007). Data in XYZ format consists of an x, y, z point file with the easting, northing, and elevation of each point describing a contour line. Data in dxf format consists of data lines describing each contour line and can be viewed through a number of GIS spatial data processing software platforms. Metadata files are available in four formats: FAQ (Frequently Anticipated Questions), HTML, text, and XML.

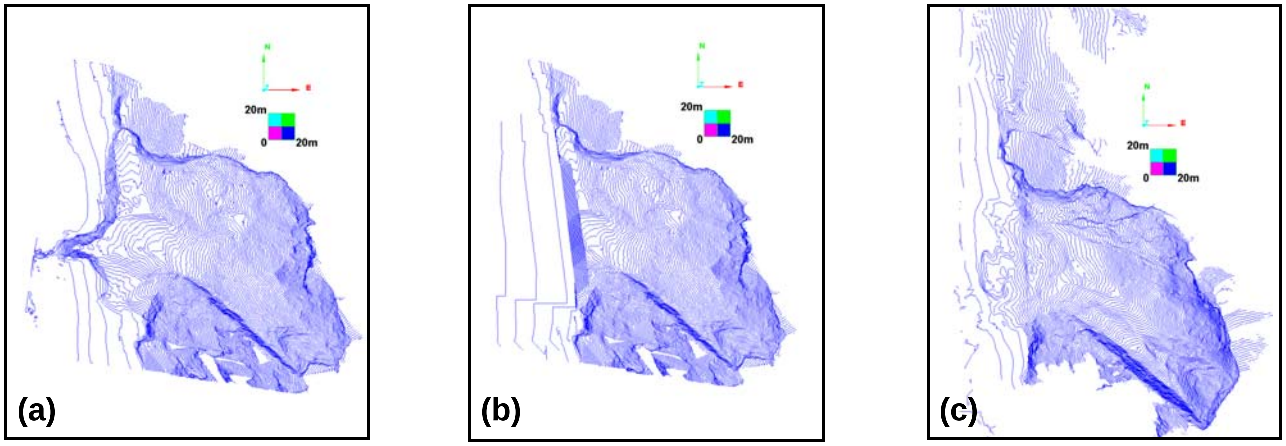

Figure 15. Graphics of 1-meter interval contour data available for the Northridge Bluff Landslide LIDAR surfaces (a) December 2003 event, (b) Pre-2007 event, and (c) January 2007 event.

Several sources of error are present in this data and must be considered when using either the points or their associated surfaces for sources of linear and volumetric measurements. These errors include those from the laser instrument (1.5 cm), those from survey control (2 to 3 cm), and those from the registration process (10 cm). Overall point accuracy relative to its true position is the sum total of these errors and estimated to be approximately 15 cm. Linear measurements between any two points of each data set therefore could contain twice this magnitude error (30 cm). However, linear measurements between any two points within a single point cloud from a single scanner location only contain twice the laser instrument error, or 3 cm total.

Table 3. Topographic 1-meter Interval Contour Data for Northridge Bluff Landslide Surfaces

Universal Transverse Mercator Coordinates (NAD83, UTM Zone10N, Metric, NAVD88, Metric)				
Landslide Event Surface	**Image**	**XYZ Format (.txt)**	**Drawing Interchange Format (.dxf)**	**Metadata Files**
December 2003 Event Surface	Dec2003 Contour Map.jpg	NBL – 1m contours Dec2003event XYZ.zip (2.5 Mb compressed, 8.7 Mb uncompressed)	NBL – 1m contours Dec2003event DXF.zip (4.2 Mb compressed, 61.6 Mb uncompressed)	NRidgeBluffDec2003.faq.html NRidgeBluffDec2003.html NRidgeBluffDec2003.txt NRidgeBluffDec2003.xml
Pre-2007 Event Surface	Pre2007 Contour Map.jpg	NBL – 1m contours Pre2007event XYZ.zip (2.2 Mb compressed, 7.6 Mb uncompressed)	NBL – 1m contours Pre2007event DXF.zip (3.7 Mb compressed, 54.9 Mb uncompressed)	NRidgeBluffJan2007.faq.html NRidgeBluffJan2007.html NRidgeBluffJan2007.txt NRidgeBluffJan2007..xml
January 2007 Event Surface	Jan2007 Contour Map.jpg	NBL – 1m contours Jan2007event XYZ.zip (2.6 Mb compressed, 9.1 Mb uncompressed)	NBL – 1m contours Jan2007event DXF.zip (4.5 Mb compressed, 65.0 Mb uncompressed)	NRidgeBluffPre2007.faq.html NRidgeBluffPre2007.html NRidgeBluffPre2007.txt NRidgeBluffPre2007.xml

Cross-sections and Volumes

Three cross-sections developed from the processed LIDAR surfaces show the geomorphology of each landslide event and indicate the magnitude of changes within the landslide mass. Two of the cross-sections (A-A' and B-B') are aligned to coincide with cross-sections analyzed in previous investigations (Cotton, Shires, and Associates, 2004b) and run southeast-northwest and east-west respectively (Fig. 16, 17, 18). The third section (C-C') runs slightly askew to section A'A' and captures the morphology of the northern portion of the head scarp where maximum crest retreat occurred in the 2007 event (Fig. 16, 19).

The cross-sections show that the 2007 event removed a large amount of the debris left within the landslide area following the 2003 landslide. Average change between the two post-event debris surfaces was 8 meters (measured vertically) with localized areas reaching 14 meters depth. The maximum mobilized landslide mass is estimated to be about 12 meters thick (measured slope-perpendicular); however, because the location of the 2007 event failure plane is not known, this is a minimum estimate. Although the 2007 event occurred almost entirely within the footprint of the 2003 landslide area, additional crest retreat did occur on the northern and southern head scarps (~1.5 meters) and to a much larger extent within the central head scarp (~9.3 meters). The maximum change was detected within this central area (Section C'C'). Average slope inclinations of the post-event profiles decreased only slightly from 40° to 38°; however, inclinations of the upper head scarp area increased by 5° to approximately 50° and locally to 90° (vertical).

Changes in volume between the post-failure debris surfaces were computed by direct comparison of the LIDAR-derived model surfaces using a prismatic volume computation algorithm (I-SiTE, 2007). This algorithm calculates the prismatic volume between each contributing triangular facet for each surface and is considered more exact and robust compared with gridding techniques. The volume computed between the post-December 2003 event but pre-2007 surface and the post-January

2007 event surface was 120,800 cubic meters. Because the location of the 2007 event failure plane is not known, this volume represents a minimum estimate of the 2007 landslide volume. Calculations also show that 20,700 cubic metes of debris were deposited on the beach at the toe of the landslide from the 2007 event.

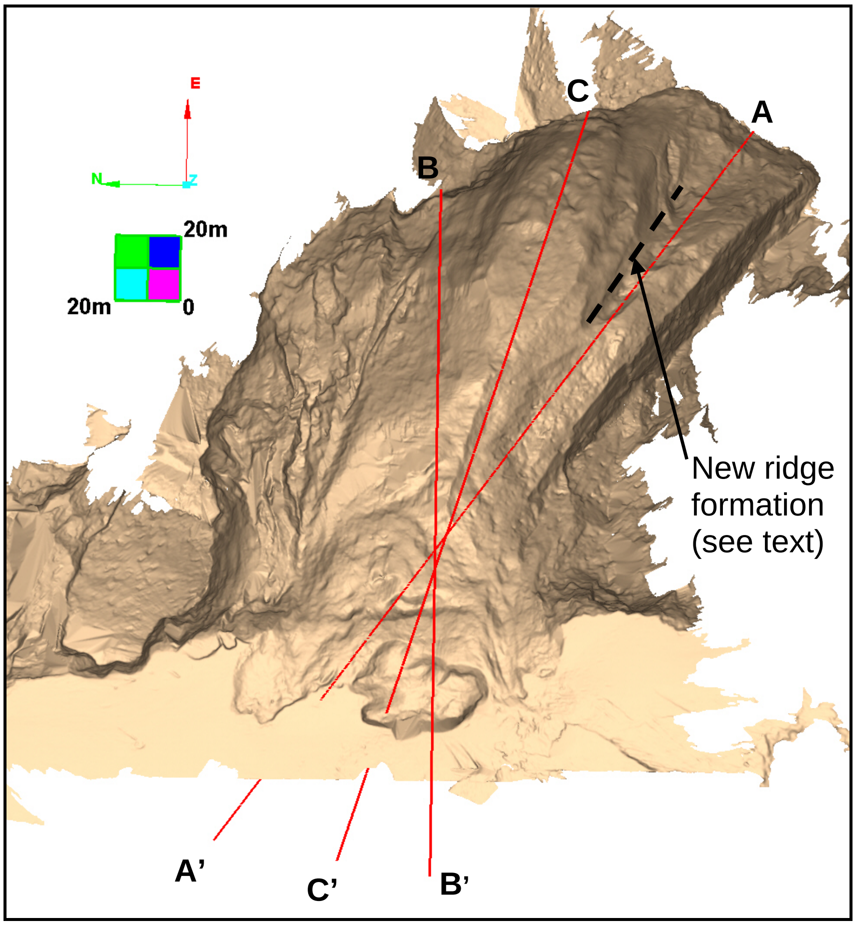

Figure 16. Location of cross sections of the Northridge Bluff Landslide. Base map is the 2007 event surface.

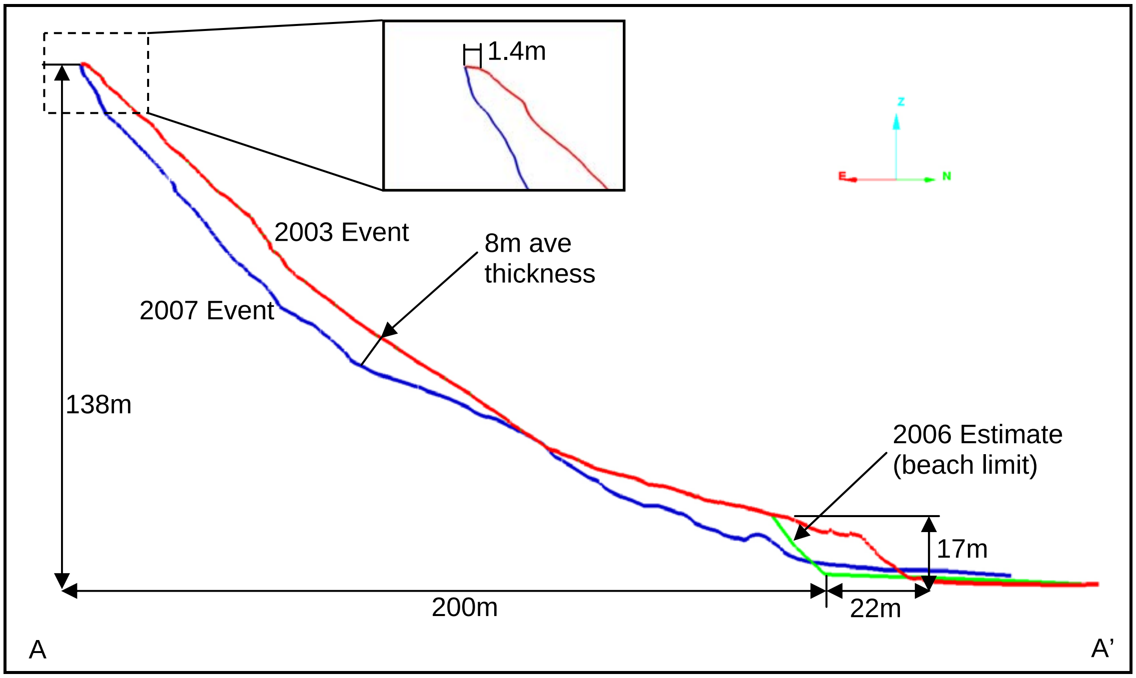

Figure 17. Cross-section A-A' (southeast-northwest) showing post-2003 event (red), post-2007 event (blue), and assumed pre-2007 event toe geometry (green).

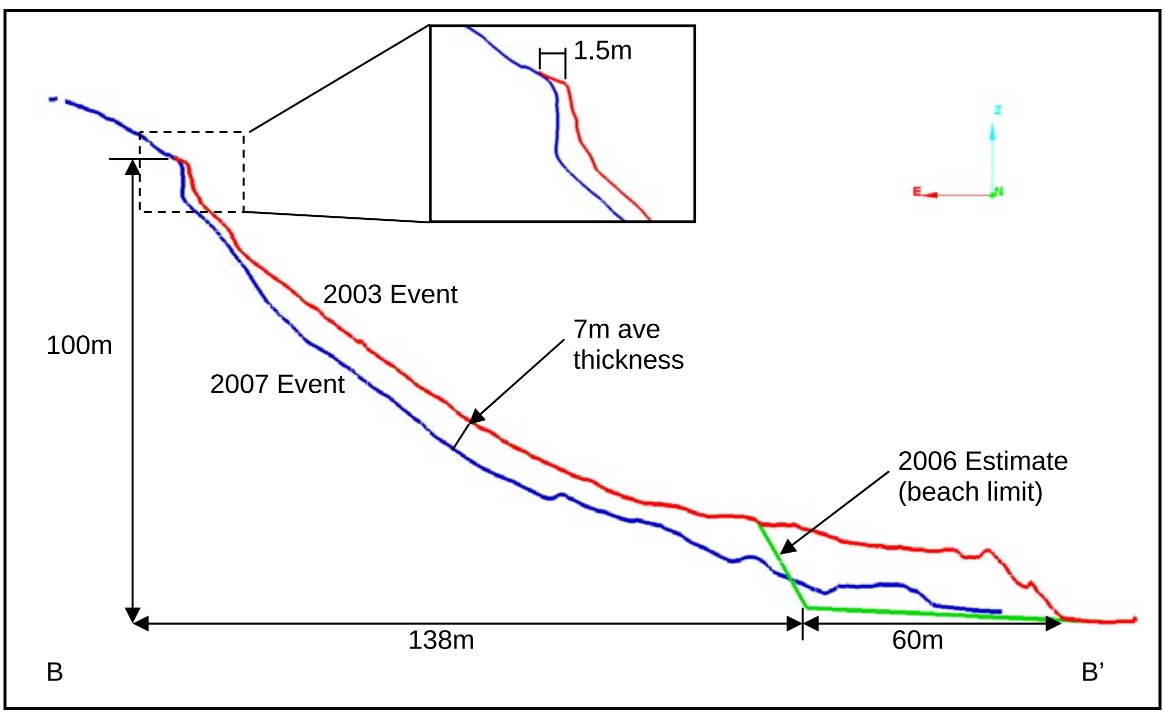

Figure 18. Cross-section B-B' (east-west) showing post-2003 event (red), post-2007 event (blue), and assumed pre-2007 event toe geometry (green).

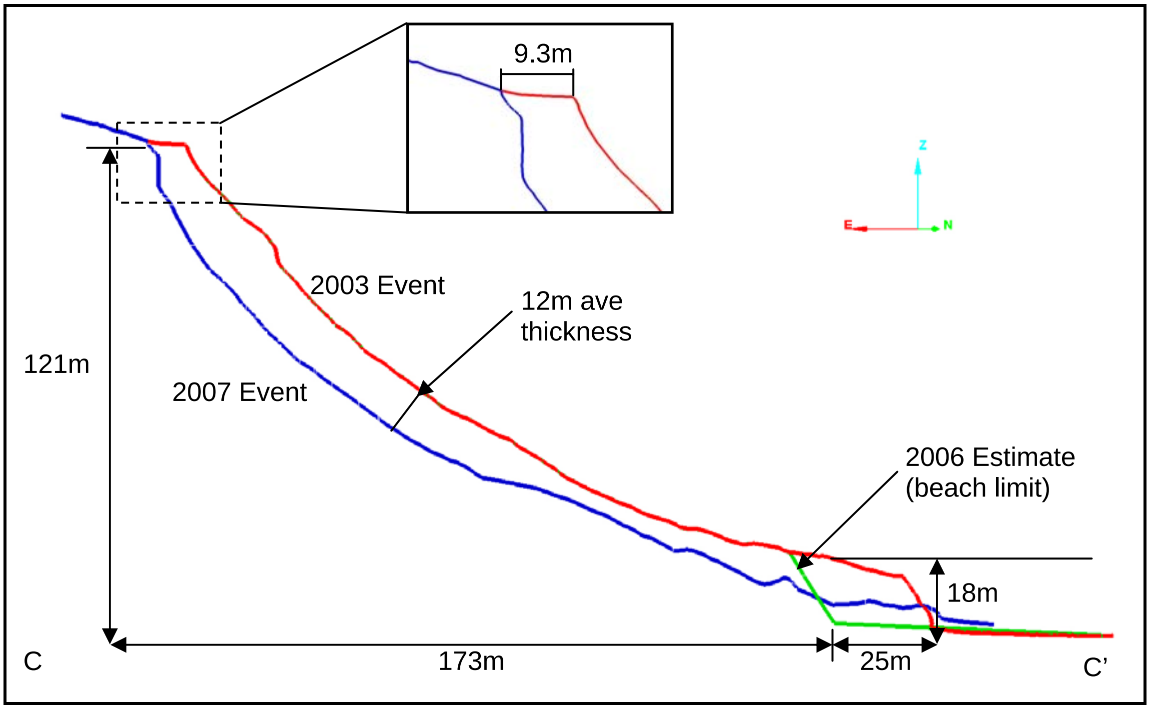

Figure 19. Cross-section C-C' (west northwest – east southeast) showing post-2003 event (red), post-2007 event (blue), and assumed pre-2007 event toe geometry (green).

Discussion

The results of the terrestrial LIDAR investigation on the Northridge Bluff Landslide show that the 2007 event was a reactivation of the 2003 landslide, of smaller magnitude and almost entirely contained within the footprint of the existing 2003 landslide scarp. Prior estimates of the original January 2003 event indicate that between 305,800 and 382,300 cubic meters of material was mobilized (Cotton, Shires, and Associates, 2004a,b). The 2007 event mobilized a minimum estimate of 120,800 cubic meters, or approximately 35% of the 2003 volume; most of this material was likely remaining debris of the initial 2003 landslide. However, new earth material was mobilized in the 2007 event, especially in the central head scarp area, where over 9 meters of crest retreat occurred and where development of a deepened post-failure surface now exists. Both of these events contributed a large volume of sediment to the beach and littoral zone, representing an important local source of sediment input. The 2003 event contributed at least 20,700 cubic meters (measured post-mobilization) to near shore deposition alone. Of importance to interpreting these dimensions and volumes is that the results do not account for minor erosion and other surface change that occurred between the dates in which LIDAR data was collected. In reality, direct observations, along with oblique photos, show that some surface change did occur following the 2003 event and prior to the 2007 event (Fig. 20). Head scarp erosion in the northeast corner, along with movement of debris towards the toe of the slide can be identified. However, our analyses show that these changes were minor to the overall geomorphology of the data presented here.

A surface change map (Fig. 21), contoured according to the change in elevation between the 2003 and 2007 event surfaces, shows the relative change in elevation from landsliding throughout the area. The data shows that the main failure mass initiated from the upper two-thirds of the slope with an average elevation decrease between the 2003 and 2007 events of about 8 meters. This represents a minimum depth of landsliding due to the unknown location of the failure plane (i.e. if the failure plane

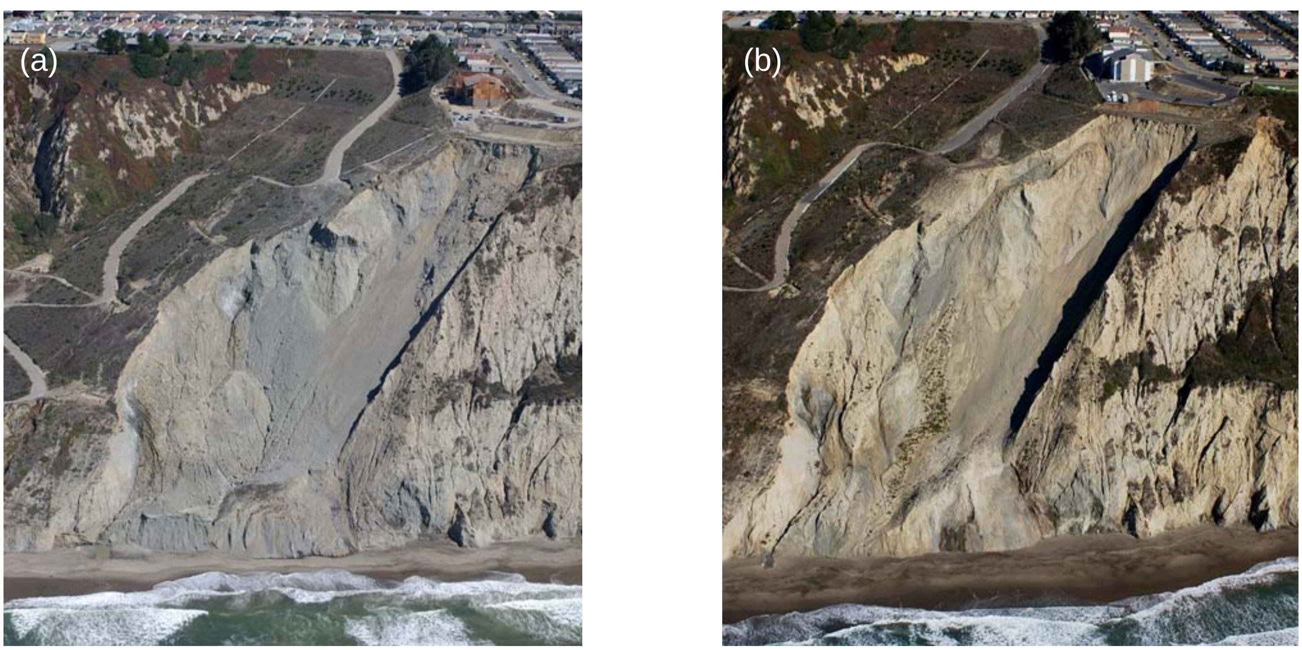

Figure 20. Oblique photos showing overall change in surface morphology between (a) September 2004, and (b) October 2005. Movement of debris from upper to lower portions of the slope are visible.

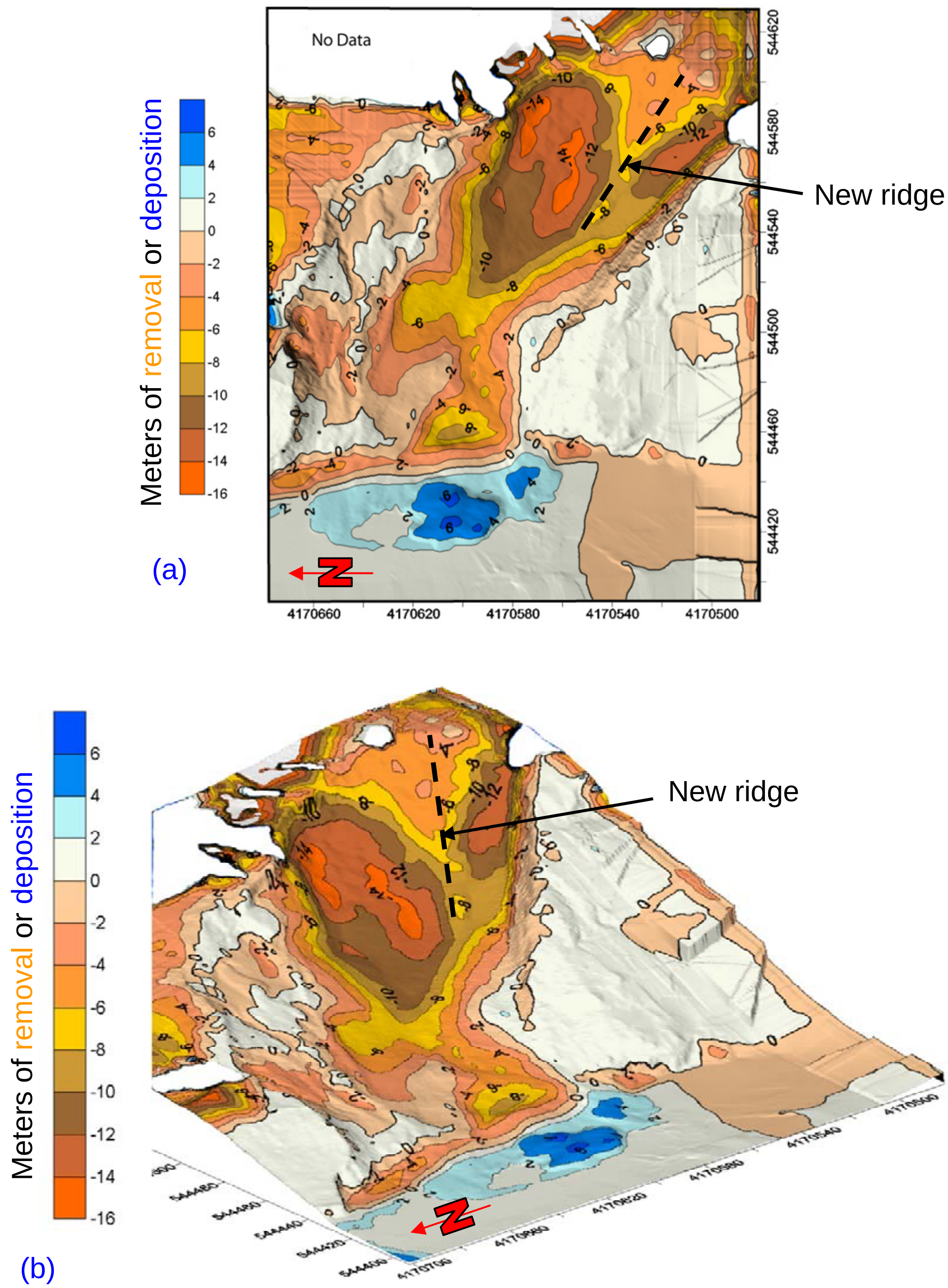

Figure 21. Change in ground surface (measured vertically, in meters) caused by the January 1, 2007 landslide event: (a) plan view, (b) oblique view - orientation is similar to Figure 14(b). Negative values (orange) indicate material removed by landslide; positive values (blue) indicate landslide deposition at the toe, or lack of data for at least one surface in regions near the crest.

is deeper than the 2007 post-event surface, the failure volume will increase to include this material). Assuming only minor surface change following the 2003 event and prior to the 2007 event, the maximum change in elevation from landsliding in 2007 was a decrease in excess of 14 meters, measured in the north head scarp area. The prominent ridge forming the south boundary of the slide was largely unchanged in the 2007 event, although the scarp did become deeper on the ridge's flank.

Of particular note is the development of a two-tongued area within the head scarp showing the development of a ridge separating the northern head scarp from the resistant bedrock ridge to the south (Fig 16 and 21). This ridge is likely composed of a stronger bed within the Merced Formation, similar to the pronounced and exposed ridge that forms the south edge of the landslide area. Depending on the lithology of the new separating ridge, this ridge could either become more pronounced over time (if the lithology is strong) or be a potential site for future mass movement (if the lithology is weak or similar to neighboring geologic units).

Analysis of the terrestrial LIDAR-derived cross-sections indicate that localized oversteepening of head scarp areas visible following the 2003 event, reformed in the 2007 event. Whereas the cross-sections show that the lower two-thirds of the landslide area is at least temporarily stable (slope inclination averaging 25°) with respect to the angle of repose of typical loose silty sand materials (27° to 30°) (Craig, 1992), the landslide mass is likely to continue to evolve under the effects of wave action at the toe and establishment of stress equilibrium at the crest.

Conclusions

As part of a comprehensive investigation of landslides occurring in weakly lithified sediments along the west coast of the United States, we conducted terrestrial LIDAR investigations of two landslide events encompassing the 2003 Northridge Bluff Landslide and it's reactivation in 2007 to make volumetric measurements and analyze geomorphologic change of a large coastal landslide affecting the west boundary of Daly City, California. Results indicate that the 2007 event was at least a third the size of the 2003 event, mobilized both existing debris and intact materials, and led to over 9 meters of crest retreat in select areas of the head scarp. In addition, volumetric measurements show that the landslide events deposited a significant volume of material to the coastal zone. The cross-section data show that as of early 2007, slope angles in the lower two-thirds of the landslide average 25° while slopes in the upper third of the bluff reach upwards of 50° and to locally 90° (vertical).

The results of this investigation show that the Northridge Bluff Landslide continues to evolve in response to both establishing overall equilibrium and to continued toe erosion from wave action. While the 2007 event is interpreted to be a reactivation of the 2003 event and a move towards equilibrium of the bluff, the magnitude of the changes are of sufficient order to anticipate further change. When weakly lithified sediments are tectonically warped, uplifted, and subject to a dynamic coastal environment, recurring landslides of this type can be expected.

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