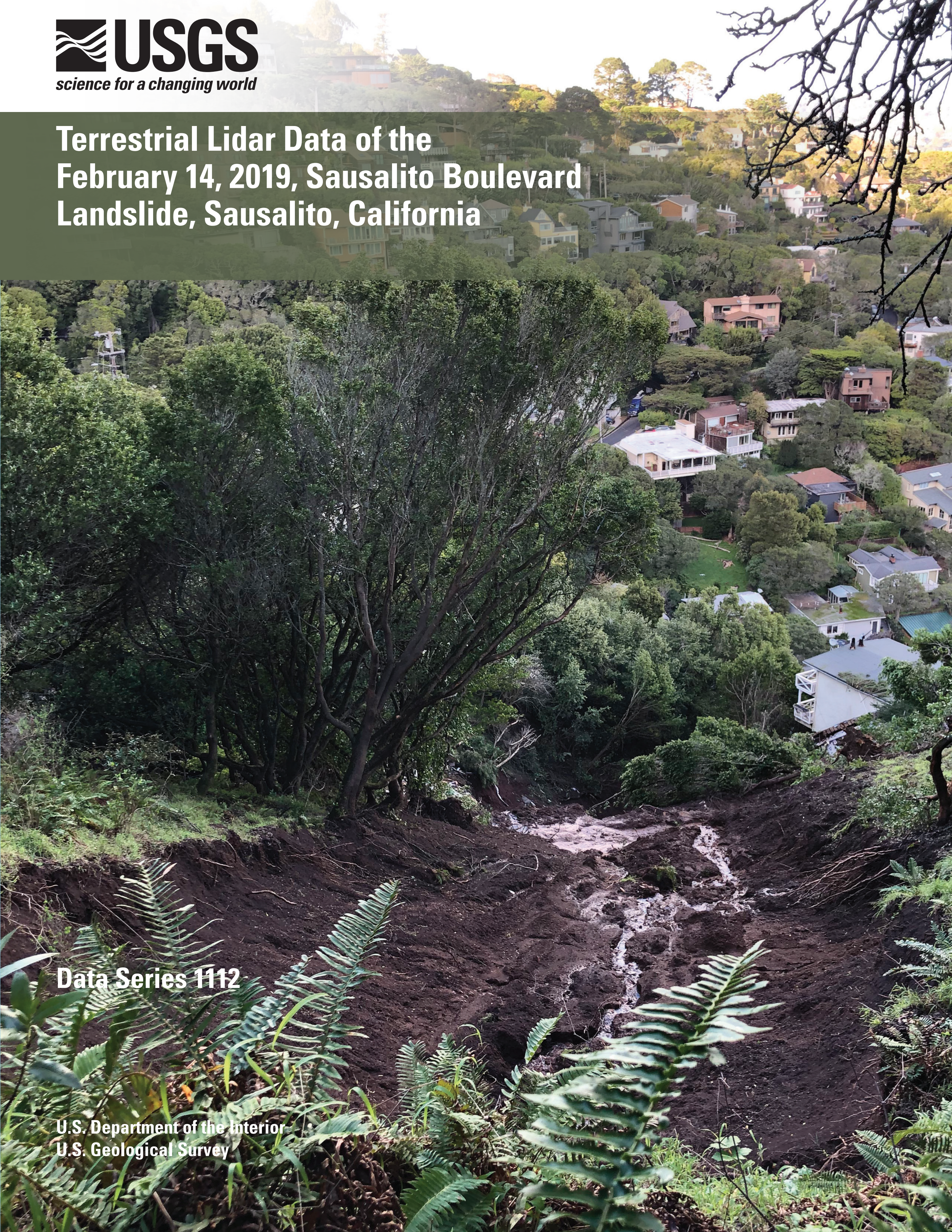

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Terrestrial Lidar Data of the February 14, 2019, Sausalito Boulevard Landslide, Sausalito, California

Data Series 1112

U.S. Department of the Interior
U.S. Geological Survey

COVER

Photograph of the February 14, 2019, Sausalito Boulevard landslide looking northeastward towards the city of Sausalito. The length of the landslide visible in this photo is approximately 60 meters, as measured between the headscarp (foreground) and Sausalito Boulevard (middle-ground). Date of image is February 15, 2019.

Terrestrial Lidar Data of the February 14, 2019, Sausalito Boulevard Landslide, Sausalito, California

By Brian D. Collins and Skye C. Corbett

Data Series 1112

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
DAVID BERNHARDT, Acting Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2019

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)

Datum

Horizontal coordinate information is referenced to the North American Datum of 1983–National Adjustment of 2011 (NAD83(2011)) and projected to Universal Transverse Mercator (UTM) Zone 10N coordinates in metric units.

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) in metric units. Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

ASCII	American Standard Code for Information Interchange
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NPS	National Park Service
OPUS	online positioning user service
RTK	real-time-kinematic
TIN	triangulated irregular network
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Terrestrial Lidar Data of the February 14, 2019, Sausalito Boulevard Landslide, Sausalito, California

By Brian D. Collins and Skye C. Corbett

Introduction

On February 14, 2019, just before 2:56 am local time (Pacific Standard Time), a landslide initiated from the hillslopes above the Hurricane Gulch section of the City of Sausalito, Marin County, California (fig. 1). The landslide, specifically classified as a debris flow, overran a road (Sausalito Boulevard) immediately below the landslide source area (fig. 2) and impacted a residential structure that subsequently toppled downslope and collided with another residential structure. The second structure then crossed a lower road (Crescent Avenue) that runs along the base of the slope before the mixture of soil and structural debris came to rest in and near the valley axis that drains the lower area of Hurricane Gulch.

Figure 1. Site map of the February 14, 2019, Sausalito Boulevard landslide in Sausalito, Marin County, California. Red star shows approximate location of the landslide. Latitude and longitude tick marks (in World Geodetic Datum of 1984 coordinates, WGS84) are for general reference.

Figure 2. Photograph showing partial landslide source area and region of one destroyed residential structure. The landslide traveled from the upper right side of the image, crossed the road (flat area in middle ground), and impacted one residential structure before subsequently carrying debris and vehicles from several partially impacted homes farther down the slope (towards the bottom left of the image). Date of image is February 14, 2019.

A resident was located in the upper level of the first impacted structure (fig. 3*A*) and survived the disaster. No residents were located in the second impacted structure. Several other residential structures were damaged as a result of passage of the debris flow below Sausalito Boulevard, and emergency officials evacuated several residents from neighboring partially damaged structures. Overall, 50 residences were evacuated due to the threat posed by potential ongoing instability of the slope and natural gas leaks from broken pipes leading to residential structures. At least seven vehicles were entrained in the debris (fig. 3*B*), due to the destruction of elevated carports attached to structures impacted just below Sausalito Boulevard.

The U.S. Geological Survey (USGS) responded to this event (herein referred to as the February 14, 2019, Sausalito Boulevard landslide) within hours of the landslide and provided situational awareness of possible secondary landslide hazards associated with the unstable slope. The USGS also rapidly mobilized its topographic surveying capabilities (specifically, GPS and terrestrial lidar devices) and collected a three-dimensional point cloud model of the landslide source area and surrounding terrain to capture the as-failed condition of the slope for use in potential future studies. This report summarizes the methods and available data collected during this response.

A

Figure 3. Photographs showing damage from the landslide that involved several homes and vehicles. *A*, View looking to the northeast towards Angel Island in San Francisco Bay. The area of one destroyed residential structure is in the foreground. The other destroyed home is located near the center of the image, which is out of site behind trees. *B*, Several vehicles were entrained within the debris amidst soil, trees, and structural debris. Area shown in (*B*) is located in the center left of (*A*). Date of both images is February 14, 2019.

Topographic and Geomorphologic Setting

The February 14, 2019, Sausalito Boulevard landslide occurred on an approximately 32°, heavily vegetated slope that is part of the National Park Service (NPS) Golden Gate National Recreation Area. The slope is located within a section of relief that descends to the northeast to less steep areas of the City of Sausalito (approximate elevation 55 meters (m) at the location of the lower destroyed residence) and upwards to the ridgeline (approximate elevation 270 m) above U.S. Highway 101 (fig. 1). The highway extends northwest to southeast and forms an anthropogenic bench in the topography (also called the Waldo Grade). The highway also runs parallel to a prominent ridge (Wolfback Ridge) in the hills forming the Marin Headlands west and above the City of Sausalito. Approximately 180 m southwest of the landslide headscarp, the highway enters the twin-bore Robin Williams Tunnels. Highway 101 is located approximately 60 m (ground distance) above the landslide source area at an approximate elevation of 160 m. An unpaved, one-lane, and limited access road (Hecht Avenue) is located just above (25 m ground distance) the landslide source area at an approximate elevation of 145 m.

The landslide source area begins at an elevation of 126 m and extends for a ground distance of approximately 50 m downslope (as measured from the headscarp to just above Sausalito Boulevard) to an elevation of approximately 102 m. The source area is approximately 12 m wide and 2 to 6 meters in thickness (fig. 4*A*). The landslide occurred on the northwest-facing sideslope of a small (100-m-wide) valley flanked by two small (100-m-wide, 200-m-long) ridges that extend to the northeast from Wolfback Ridge. The northwest-facing slope of the ridge encompassing the landslide source area is composed of several slightly convergent swales (characterized as colluvial-filled hollows; for example, see Dietrich and others, 1986). The landslide initiated from one of these hollows. Following initiation, the landslide dropped over a steep (approximately 49°) 6-m-tall slope, overran Sausalito Boulevard, impacted a residential structure (duplex), and continued downslope. Very little deposition of debris above Sausalito Boulevard was observed (that is, the source area encompasses almost the entire landslide zone above the road and exhibits near complete evacuation of all debris). The landslide deposit zone extends from Sausalito Boulevard (approximate elevation 93 m) 30 m down an approximately 36° slope to the less steep valley floor. The deposit then flowed onto the lower angle (~20°) valley floor and eventually stopped just past Crescent Avenue, where the debris collided with another residential structure. Total ground length of the source and runout zone (as measured from the headscarp to the distal end of the deposit) is approximately 220 m. Total elevation difference over this distance is approximately 75 m.

Methods

Data Collection, Registration, and Georeferencing

We collected terrestrial lidar of the Sausalito landslide source area on Sunday, February 24, 2019, 10 days following the landslide. Terrestrial lidar is a survey technique that uses a pulsed laser to measure the distance to any reflective object by measuring the time of travel of the projected and received laser return. Combined with integrated precision devices that measure the orientation of the laser about the instruments origin, terrestrial lidar is capable of capturing millions of three-dimensional points of virtually any landscape in a matter of minutes. The resultant data—often termed a “point cloud”—allows for the geometric reconstruction of complex terrain. It also offers a way to survey hazardous topography. The resulting oversteepened surfaces of the landslide headscarp above Sausalito Boulevard (fig. 4*B*) may have been unstable, and we used terrestrial lidar to capture these data from positions distant from these areas.

We focused our efforts on the landslide source area to capture the as-failed geometry of the landslide. Although some of our data captures the landslide deposit area below Sausalito Boulevard, most of this area was not directly visible from our laser setup locations on and above the road. Using a Riegl Z420i terrestrial lidar instrument (fig. 5), we collected data from six independent laser scan (LS) positions—three on Sausalito Boulevard and three from the margins of the landslide source area (fig. 6). Scanning at a resolution of 0.08 to 0.1 degrees in both horizontal and vertical directions, each scan position provided approximately 3 million data points of the surrounding terrain. At a mean scan distance of 30 m from laser to point of reflectance, the mean spot size (area of sampling) is approximately 0.4 cm^2 for each point measurement. The error associated with laser return positions (E_{laser}) is approximately 1.0 cm (based on the manufacturer’s reported accuracy of the laser instrument for 1σ (~68%) standard deviation at 50 m range).

To combine data from independent scan positions, we used five control points (CP) (10 cm tall, 10 cm diameter cylindrical reflectors, fig. 7) distributed along Sausalito Boulevard and the margins of the landslide source area (fig. 6). Using the default registration algorithm in our processing software (Riegl RiScan Pro), we obtained a mean registration error (E_{reg}) of 0.3 cm for all scans combined with one another.

We used a pair of Topcon Hyper+ GPS devices (base + rover) operating in real-time-kinematic (RTK) mode to collect dual band (L1+L2) differentially corrected positions of all laser scan and control point locations.

A

B

Figure 4. *A*, Photographs showing landslide source area as viewed from the headscarp. A prominent stream of water exited the headscarp and flowed along the landslide axis in the days following the landslide. Sausalito Boulevard is located at the bottom of the slope (middle ground of image). Width of landslide is approximately 12 meters. *B,* The landslide headscarp forms a near-vertical slope approximately 6 meters tall. Photograph (*B*) by Bryant Ho (City of Sausalito)

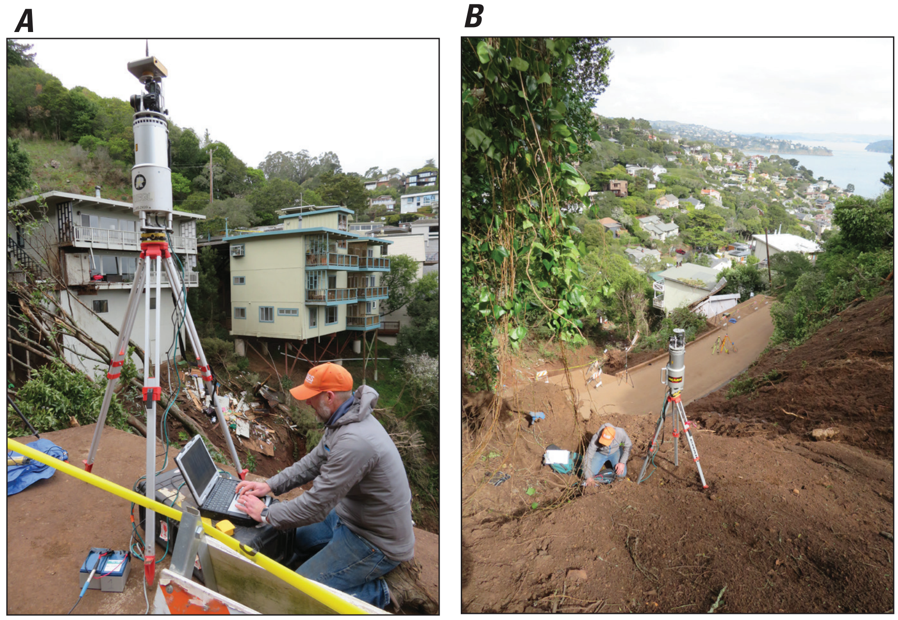

Figure 5. Photographs of a terrestrial lidar survey in progress from (*A*), Sausalito Boulevard, and (*B*), the left (west) margin of the landslide source area. The laser is mounted on a leveled tripod and a camera with fish-eye lens is mounted on top to capture imagery for post-processing the color of the point cloud. In (*A*), the RTK GPS rover is mounted above the camera for collection of precision survey data of the instrument location.

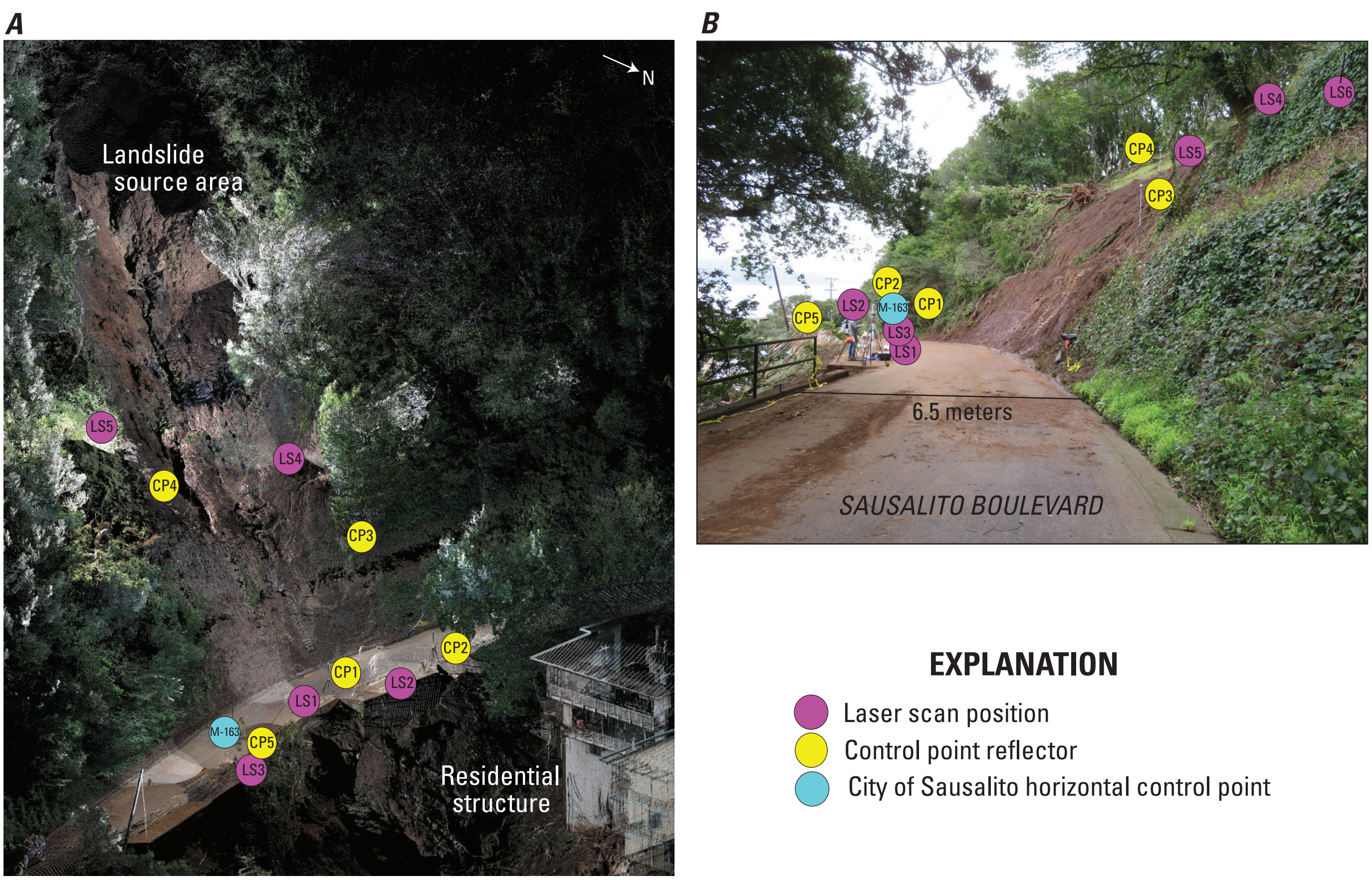

Figure 6. Image of *A*, Point-cloud-based site map and *B*, image of Sausalito Boulevard looking eastward, showing location of laser scan positions (LS#), control point reflector locations (CP#), and the horizontal control point (M-163) used for positioning our GPS base station relative to the landslide source area. Laser scan position LS6 is not visible in (*A*) under the trees on the west upper margin of the landslide.

Figure 7. Photograph showing GPS base station (neon yellow tripod) with radio mast antenna (yellow and orange tripod) set up over control point M-163 on Sausalito Boulevard. Terrestrial lidar data collection from position LS1 is taking place and several control points (white cylinders on black and silver tripods) are visible in the background.

We located our base station over a City of Sausalito horizontal control point (M-163, fig. 7; NAD27 (North American Datum of 1927) California State Plane Zone 3 horizontal coordinates E1426810.90 ft, N496963.32 ft), but performed a 6-hour static GPS collection to obtain an independent coordinate solution in NAD83(2011) (North American Datum of 1983–National Adjustment of 2011), UTM (Universal Transverse Mercator) Zone 10N coordinates (in meters). The static solution was processed by the National Geodetic Survey's online positioning user service (OPUS) processing algorithms (https://www.ngs.noaa.gov/OPUS/). We used the GEOID12B geoid (https://www.ngs.noaa.gov/GEOID/GEOID12B/) output from OPUS to transform the ellipsoid solution for the base station control point to an orthometric height in NAVD88 (North American Vertical Datum of 1988) coordinates (in meters). All laser and control points are thereby referenced to this set of coordinates (NAD83(2011)-UTM Zone 10N and NAVD88). Overall accuracy of the static OPUS solution (that is, the error associated with the global control network, $E_{control}$) is 2.0 cm. Overall three-dimensional accuracy of our internal network RTK solutions (that is, the error associated with the measurement of positions between the base station and rover locations, E_{survey}) is 0.8 cm (ignoring one laser scan position, LS4 that we were not able to obtain a fixed GPS solution for). We were able to obtain subcentimeter solutions for all but three points (LS4 – 3.4 cm, LS6 – 1.5 cm, and CP3 – 1.6 cm)—these were located under heavy vegetation on the left lateral margin of the landslide source area with poor visibility to the sky. Applying the georeferenced coordinates from the laser scan (5 of 6 points, excluding LS4) and control points (5 of 5 points) to the point cloud data resulted in a final georeferencing error (E_{georef}) of 2.3 cm.

To calculate the overall accuracy of the final data products, we use error analysis protocols by Collins and others (2014). These protocols outline how errors from the laser instrument, registration process, georeferencing procedures, survey network, and global control network should be combined to estimate the overall accuracy of terrestrial lidar data. The methodology uses a root mean square error formula, shown in equations 1 and 2, as an estimate of either local (E_{local}, internal to the data set; that is, E_{laser} and E_{reg} only) or global (E_{global}, between the data set and other georeferenced data; that is, E_{laser}, E_{georef}, E_{survey}, and $E_{control}$) measurements made using the point cloud data. The registration error (E_{reg}) is ignored for the external accuracy calculation because it only represents how close the points are within the dataset itself—the georeferencing error captures this error when comparing the data to external data sources such as airborne point cloud models.

$$E_{local} = \sqrt{(E_{laser})^2 + (E_{reg})^2} \quad (1)$$

$$E_{global} = \sqrt{(E_{laser})^2 + (E_{georef})^2 + (E_{survey})^2 + (E_{control})^2} \quad (2)$$

For

laser error (E_{laser}) of 1.0 cm;
registration error (E_{reg}) of 0.3 cm;
georeferencing error (E_{georef}) of 2.3 cm;
survey error (E_{survey}) of 0.8 cm;
and control network error ($E_{control}$) of 2.0 cm,

the resultant local error is 1.0 cm and the resultant global error is 3.3 cm.

We note that these error assessments are based on possible errors in the data sets. It is highly unlikely that all errors are independent, or that they are always additive in the same direction. Thus, we find this error analysis more reasonable than adding all maximum errors together (that is, 6.4 cm). We further note that these accuracies are based on data registration procedures performed locally to the landslide. Far-field data contained in the point clouds of the surrounding Hurricane Gulch neighborhood may not be accurate to these specifications.

Data Filtering

Point cloud data are subject to extraneous data from a number of sources that must be filtered (that is, removed) to obtain a reliable and user-friendly data product. Depending on the type of data that needs to be filtered, both manual and automated algorithms are available. To achieve a final "all points" data product (that is, a product that includes all objects in the scene, such as the ground, trees, and structures), we used manual filtering techniques within a point cloud software program (Maptek I-Site Studio version 5.1) to remove points from airborne water vapor and dust, birds, and people in the scene. We also manually deleted points representing tarps, ropes, and sand bags that were being installed on the headscarp of the landslide at the time of the survey. These objects were only visible from a few scan positions, and since they did not reflect the underlying ground data, they were deemed unnecessary to include in the final data product.

To obtain a bare-earth point cloud (that is, a point cloud with all vegetation and structures removed), we applied a more complicated methodology that utilizes a series of semiautomated filtering steps to remove points representing objects other than the ground surface. Using the same point cloud software program as previously described, we performed the following steps:

1. Beginning with the "all points" data, we applied a lowest point (topography) filter on a 1m grid and removed all other higher elevation points.

2. We created a triangulated irregular network (TIN) surface of the points from step 1 using a maximum boundary triangle length of 3 m. We subsequently

despiked (removed anomalous high or low points from) this surface.

3. Starting with the “all points” data again, we selected only points that were within 0.3 m of the TIN surface from Step 2 (surface proximity filter).

4. Using the point data set from Step 3, we applied a lowest point filter on a 0.5 m grid and removed all other higher elevation points.

5. We then created a TIN surface of the points from step 4 using a maximum boundary triangle length of 2 m. We subsequently despiked (removed anomalous high points from) this surface.

6. Starting with the “all points” data a third time, we selected only points that were within 0.1 m of the TIN surface from Step 5.

7. Finally, using the point cloud data from step 6, we applied a lowest point filter on a 0.1 m grid to achieve a set of points that are representative of only the points on the ground surface within the scene.

Because the filtering algorithms utilized on the data work by removing the highest points within a given area, it is normal for points describing areas of vertical terrain (for example, landslide scarps) to be removed from the data. We mitigated this issue by manually adding the deleted vertical points back to the filtered model following the last step (step 7). This consequently added more depth and helped create a model that is more truthful to the actual ground surface.

Surface Generation

We created a bare-earth ground surface digital terrain model using the topographic surface model construction algorithm in our point cloud software program (Maptek I-Site Studio version 5.1). Here, we constructed a TIN surface, despiked the surface to remove any anomalously high or low surface points, and filled in any remaining holes in the surface with automated TIN-filling methods offered in our software.

Results

Survey Control

We present the survey point coordinates for all laser scan (LS#) and control point (CP#) locations, as well as the GPS base station bench mark (City of Sausalito point M-163) for completeness (table 1) and transparency of our surveying protocols. Note that the coordinate for which all points are based is the static GPS solution collected at M-163 on February 24, 2019, which does not coincide exactly with the City of Sausalito’s NAD27 survey point that is referenced to NAD27 and California State Plane (Zone 3) coordinates. After performing a coordinate transformation for the City’s coordinate locations, our calculations indicate a −12.6 cm difference in easting and a −16.0 cm difference in northing between our GPS solution and the City’s surveyed benchmark solution (with our GPS solution having a smaller value in both cases). These differences are expected given the different surveying techniques with which the point was measured, and are highlighted here only for aid in any future use of the data in a different coordinate system than presented here (NAD83 and UTM).

Point Data

We present two point cloud data sets for the post-failure topography of the February 14, 2019, Sausalito Boulevard landslide—one each for the all points data set and the bare-earth data set (fig. 8). The all points data set consists of six individual files that coincide with each of the six scan positions from which we collected data. Data includes points for the landslide and its surroundings, as well as for the vegetation, roads, and residential and other structures visible from the scan positions within the Hurricane Gulch neighborhood. The scan distance for these data extends to approximately 700 m from the area of the landslide in some cases. The bare-earth data set consists of one combined file of the bare-earth data for the landslide source area and its immediate surroundings. Data includes only ground surface points as defined by the point filtering methodology outlined in the Methods section of this report. The scan distance for these data extends away from the landslide scarps by about 10 to 14 m.

All point cloud data files (all point and bare-earth data sets) are in ASCII (American Standard Code for Information Interchange) .txt format. Data files are available for public download from the USGS’ Science Base catalog, an open-sourced collaborative scientific database. Data for the Sausalito Boulevard landslide can be found in Corbett and Collins (2019) accessible through Science Base.

Surface Data

The surface model data presented herein and included in the linked data files are but one possible reconstructed digital terrain model output using the point cloud data. We processed the data to generate a TIN surface model with approximate facet length of 10 cm and limited the model boundaries to just the landslide source area and surrounding terrain behind the landslide scarps (fig. 9). This model can be utilized for a variety of purposes including examining cross-sections through the landslide or to obtain the volume of the failed debris (with either a prelandslide lidar data set or a manually formed surface reconstruction).

Table 1. Table of processed georeferenced coordinates for base station, laser scan and control point locations.

Survey point name	Easting[1] X (meters)	Northing[1] Y (meters)	Elevation[2] Z (meters)
M-163 (base station)	545189.796	4189089.901	92.452
LS1	545183.327	4189090.155	95.661
LS2	545174.992	4189090.444	96.416
LS3	545195.706	4189095.806	94.238
LS4	545170.352	4189073.930	105.539
LS5	545187.977	4189067.145	110.146
LS6	545164.370	4189059.067	116.214
CP1	545180.830	4189089.082	96.081
CP2	545171.731	4189090.299	96.894
CP3	545172.804	4189079.789	101.530
CP4	545182.048	4189073.714	105.897
CP5	545194.185	4189094.776	94.528

[1]Easting and northing referenced to NAD83(2011) horizontal datum and UTM Zone 10N projection.

[2]Elevation referenced to NAVD88 vertical datum using the GEOID12B geoid applied to NAD83(2011) ellipsoid solutions. Elevation for the base station represents the indentation on the inset brass disk approximately 10 cm below the pavement surface of Sausalito Boulevard. Elevation for laser scan locations represents the base of the instrument. Elevation for control points represents the center of the cylinders.

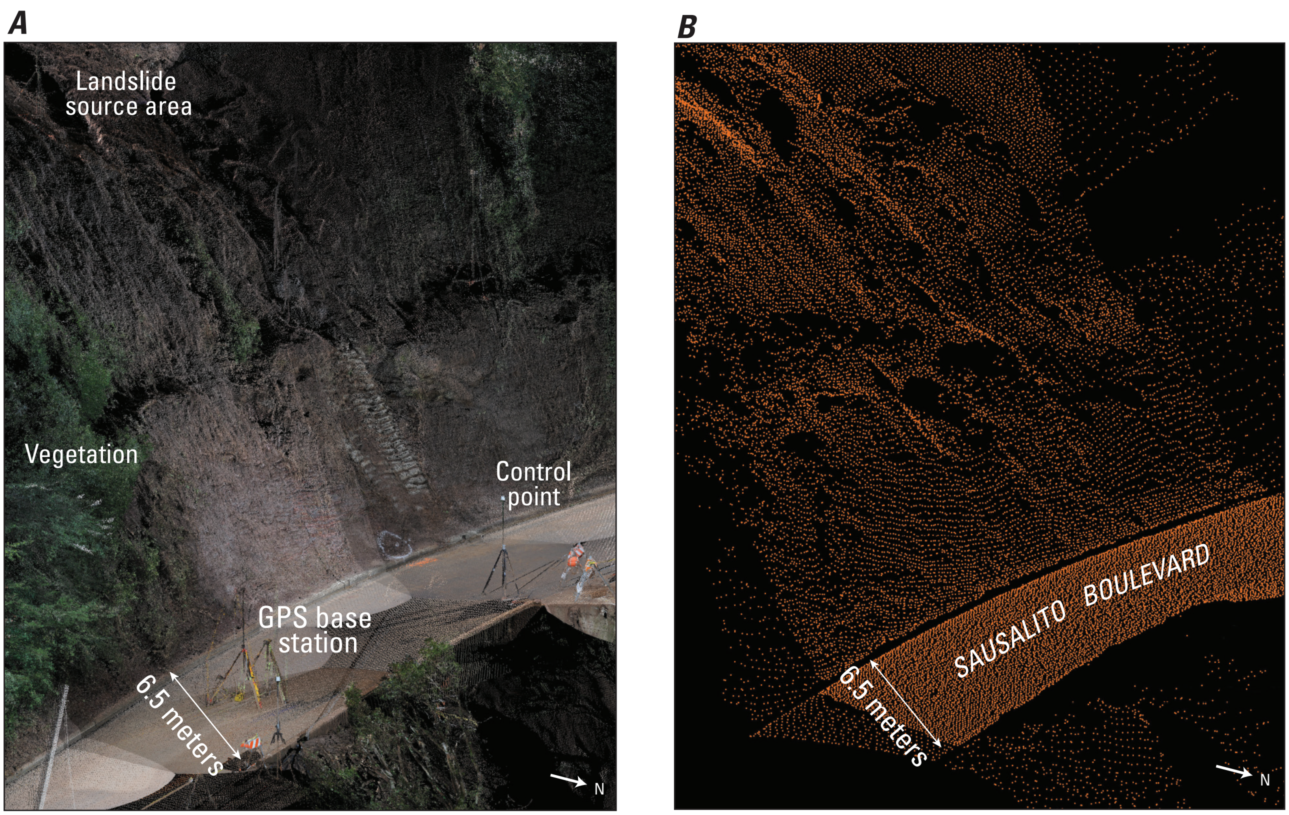

Figure 8. Images of (*A*) unfiltered and (*B*) filtered, bare-earth point cloud data of part of the landslide source area. In (*A*), data includes all points of the scene including trees, survey tripods, and road barricades. In (*B*), data only includes points representing the ground surface.

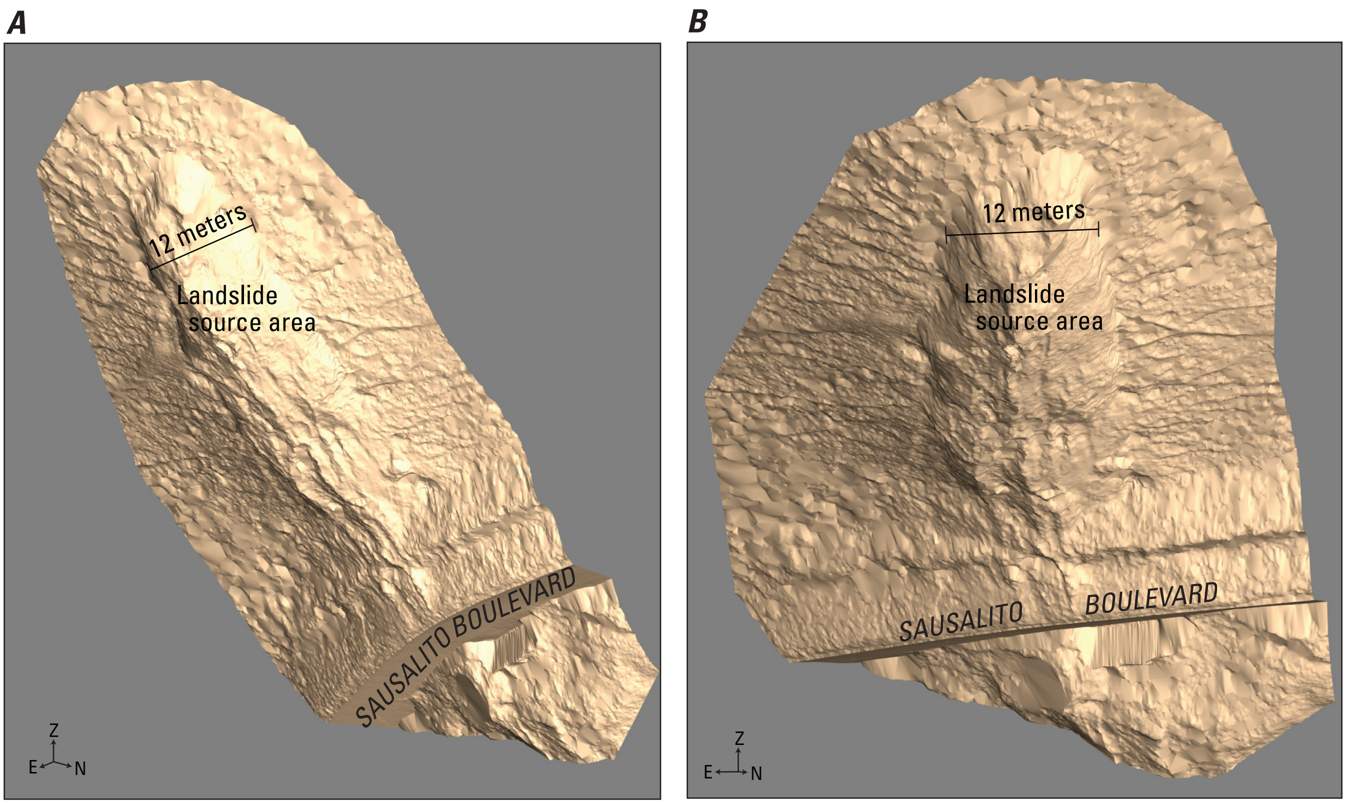

Figure 9. Images of bare-earth terrain model of the source area from two different perspectives: (*A*) looking oblique to the southwest, and (*B*) looking to the south. The model is constructed by joining points via a TIN (triangulated irregular network). Other types of surface models can also be generated using either the point data, or resampling of the TIN model.

The presented surface model is in .dxf format (drawing exchange format; see https://www.loc.gov/preservation/digital/formats/fdd/fdd000446.shtml) and is available for public download from the USGS' Science Base catalog. Data for the Sausalito Boulevard landslide can be found in Corbett and Collins (2019) accessible through Science Base.

Summary

The February 14, 2019, Sausalito Boulevard landslide in Sausalito, California caused significant destruction and damage to several residences located in the Hurricane Gulch neighborhood of the city. The landslide, composed of a debris flow from a colluvial filled hollow, completely evacuated the source area and impacted several structures before coming to rest in the lower area of the neighborhood. The USGS assisted with the emergency response to the event by providing situational awareness of secondary landslide hazards, and collecting high-resolution topographic data of the landslide source area and surrounding terrain. The data collected from this work are available in Corbett and Collins (2019) for the purposes of future investigation of the landslide.

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