

Lidar-based rock-fall hazard characterization of cliffs

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ABSTRACT

Rock falls from cliffs and other steep slopes present numerous challenges for detailed geological characterization. In steep terrain, rock-fall source areas are both dangerous and difficult to access, severely limiting the ability to make detailed structural and volumetric measurements necessary for hazard assessment. Airborne and terrestrial lidar survey methods can provide high-resolution data needed for volumetric, structural, and deformation analyses of rock falls, potentially making these analyses straightforward and routine. However, specific methods to collect, process, and analyze lidar data of steep cliffs are needed to maximize analytical accuracy and efficiency. This paper presents observations showing how lidar data sets should be collected, filtered, registered, and georeferenced to tailor their use in rock fall characterization. Additional observations concerning surface model construction, volumetric calculations, and deformation analysis are also provided.

INTRODUCTION

Rock falls from cliffs and other steep slopes present obvious hazards to persons and infrastructure located below. They also impart numerous challenges for detailed geological characterization. For example, source areas are typically both dangerous and difficult to access, thereby limiting the ability to make detailed measurements necessary for hazard assessment (Fig. 1). In addition, rock-fall source areas may be active for hours, days, and even months following an initial event. This may preclude any safe means to directly investigate key factors needed for ongoing hazard assessments such as cliff geometry, joint structure, incipient fractures, and presence of seepage. In addition, general site characterization may be limited to simple visual observations, high-resolution photographs, and in the best cases, sporadic single point measurements provided by reflectorless total station survey techniques. This may provide some helpful information about spatial location, relative size, and potentially the magnitude of ongoing movement, but only if the single point measurements capture actively deforming zones of the rock mass. Thus, the use of these methods is likely to provide limited information to geologists and engineers responsible for evaluating the hazard posed to vulnerable infrastructure, such as structures or transportation corridors located beneath rock-fall-prone cliffs.

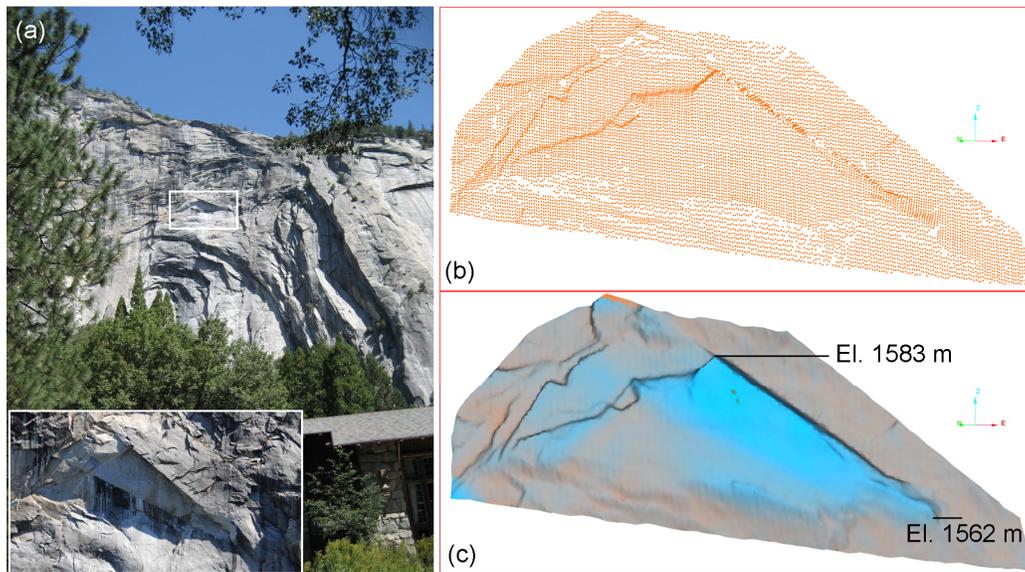


Figure 1. (a) Image of a 2009 rock-fall in Yosemite National Park with (b) point cloud and (c) surface model of the source area. Brightest-blue colored areas of surface model in (c) indicate areas of change following the rock fall.

For approximately ten years, terrestrial (ground-based) and airborne lidar (light detection and ranging) methods have revolutionized many aspects of site characterization related to geologic hazards. These include the use of lidar for volcano monitoring (Jones, 2006), post-earthquake reconnaissance (Kayen et al., 2006), and landslide characterization and monitoring (Collins and Sitar, 2004; Schulz, 2007; Oppikofer, 2009) to name a few. Its use in landslide characterization has been particularly valuable, especially where steep slopes and cliffs have been studied (e.g., Rosser et al., 2005; Lim et al., 2005; Collins and Sitar, 2008; Lan et al., 2010; Young et al., 2010; Stock et al., 2011). As various applications of lidar have rapidly developed, textbooks on the subject have recently been published (e.g., Shan and Toth, 2009; Vosselman and Maas, 2010). These books provide a valuable introduction to the subject, but rapid advances in technology and application demand that active practitioners rely on both scientific and industry journal and conference proceedings to stay abreast of the latest developments. This is especially true of applications for landslide monitoring, including rock fall characterization and monitoring. This paper presents current methods for using lidar data for geomorphologic and structural geologic studies on steep cliffs, and particularly those focused on rock-fall hazard characterization. Included are discussions of various pitfalls that are encountered in these types of projects along with suggested remedies.

TERRESTRIAL AND AIRBORNE LIDAR SURVEYING

Lidar surveying is the process of sending and receiving laser pulses to and from an object of interest. In its simplest form, the surveying process can be thought of as using a reflectorless total station or laser range finder at a very high frequency (1000's to 100,000's of measurements per second) to generate a three-dimensional model of a topographic surface. The group of points collected is often referred to as a

“point cloud”, an accurate descriptor of the dense data that results from a lidar survey (e.g., Fig. 1b). In almost all cases (terrestrial or airborne), accurate control is necessary to register (i.e., bring points collected from two or more vantage points together into a single model) and georeference the data (i.e., move the data from a local to real-world coordinate system). A registered and georeferenced data set is typically the product of a lidar survey and is necessary for overlaying other georeferenced data sets (e.g., aerial photographs or previously collected lidar data).

METHODOLOGIES FOR STEEP SLOPES AND CLIFFS

Lidar applications to steep slope and cliffs have both advantages and limitations that result from the vertical-orientation of the topography of interest. Here, these issues are presented in the context of the various stages undertaken during a typical lidar survey project: data collection, filtering, registration, georeferencing, surface model construction, volume calculation and cross-section generation, structural analysis, and change detection.

Point cloud collection and data filtering

Obtaining an appropriate point cloud data density is one of the most important issues during lidar data collection. For areas scanned from a terrestrial platform at the base of a cliff, the data density needed to adequately characterize the cliff should be determined by the ideal point-to-point spacing at the highest location within the study area. The data density will increase moving downwards in elevation due to the decreasing range for a vertical cliff (i.e., point-to-point spacing is smaller at shorter distance for the same laser angular increment). In addition, the number of laser returns will increase with laser trajectories that are less oblique (i.e., more perpendicular) to the cliff face. Thus, the data density selected at the highest portion of the cliff might decrease below this minimum if laser trajectory incidence angles are overly oblique. Ideal limits of oblique incidence angles can be estimated by general rules of thumb (i.e., laser trajectories at over 45° incidence angle are not dependable, or some other manufacturer recommendation), but generally, a test of actual field conditions is usually necessary to establish this criterion. Some surfaces are more reflective; wet surfaces are generally not. Additional consideration should also be given to the laser spot size on the target, as this will influence the accuracy of the data, especially at far range. Typically, laser power and trajectory distance are the two major contributing factors governing divergence and therefore spot size. High laser power typically decreases beam divergence, whereas long range increases divergence.

Creating a “bare ground” surface from point clouds is typically extremely difficult when working in areas of significant vegetation. Fortunately, steep cliffs generally have little to no vegetation to remove from the point cloud data. When faced with a vegetated cliff, two filtering methods can be applied. The first is manual filtering of the point cloud using a cross-section tool to view the cliff profile in sections. In this way, vegetation sometimes stands out and can be removed directly using filters embedded in high-end three-dimensional point cloud processing

software. Additionally, high resolution photographs can be used to assist in determining the precise extents of vegetation. The disadvantage of this technique is that it is labor-intensive. The second method is the use of automated techniques that either remove points that are a defined distance away from a bare-ground seed surface (e.g., remove any point that is greater than 5 cm from a base surface that has previously been created from known rock outcrops at a coarser scale) or that surpass a defined angular threshold (e.g., remove any point that is greater than 30° angular orientation from a neighboring point). This method is sometimes better implemented by rotating the data set into the horizontal plane as the filters have generally been written into software scripts designed for relatively horizontally-oriented (airborne) data. Care must be taken at the cliff base and roof intersections so that points located there are not inadvertently removed. The major disadvantages of this method are the additional point cloud manipulation required to rotate the data set and the data density (and potential feature) loss that inevitably occurs from automated methods.

Registration and georeferencing techniques

Although standard registration procedures for airborne lidar do not significantly change for steep cliff profiles, additional effort is usually required for terrestrially-collected data sets. This is due to the lack of accessible or visible survey control points (e.g., reflectors or prisms) on or at the top of cliffs, which are generally needed to link neighboring scan locations into the same local coordinate system over the area of the scan data. To avoid this issue, nearest neighbor algorithms can be used (i.e., so-called cloud-to-cloud registration or surface registration) in which identifiable features of complex topography are either manually or automatically matched over the entire overlapping area of two neighboring point clouds. This method is generally successful in obtaining an accurate registration of the data, but problems may result if nearest neighbor algorithms are utilized over long, linear distances often prevalent in cliff surveys. Here, the registration of one scan location to its neighbor, and then again from that neighbor to the next neighbor may propagate errors from previous neighbor registrations (Fig. 2a). Specific procedures have been developed to minimize these registration issues, including triangulating scan positions intermittently during scanning (Collins et al, 2006; Fig. 2b), or determining the ideal neighboring scan overlap so that neighbor least squares fitting can be optimally applied to the entire length of neighboring scans (Olsen et al, 2009; 2011).

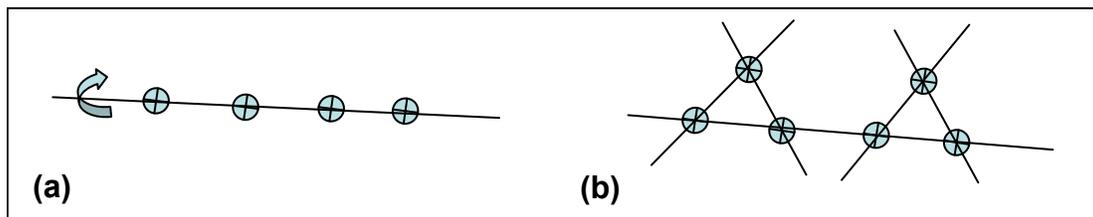


Figure 2. Terrestrial lidar registration issues associated with long, linear cliff segments. (a) Scans (circles) aligned along an axis are free to rotate along the axis. (b) Scans aligned in a triangulated network constrain the rotational degree of freedom. All points are thereby constrained in the X, Y, and Z directions.

Georeferencing procedures are affected by some of the same issues as registration techniques. For both airborne and terrestrial surveys, a thorough network of control points at the base, on the crest, and optimally in the middle of the cliff, is ideal, but not always possible. Points at differing elevations generally help to constrain vertical errors implicit in cliff surveys. Despite these challenges, registration and georeferencing errors can be minimized such that terrestrial and airborne data sets can be combined, despite their differing scan accuracies, densities, and look-angles (e.g., Stock et al., 2011). This combination provides an important added benefit of capturing horizontal, vertical, and overhanging surfaces, showcasing the power of integrated terrestrial-airborne lidar surveys (Fig. 3).

Model surface construction and volumetric and cross-section analysis

In some cases, a registered, georeferenced point cloud suffices as the final product from a lidar survey. In the point cloud, both point and distance measurements can be made, and, given sufficient point density, particular features of the rock mass such as fractures or bedding planes can be identified. However, very often a topographic model surface is required to construct continuous two-dimensional cross-sections or to calculate volume change between two or more consecutively surveyed surfaces. Model surface construction is typically performed using one of two methods: grid-based digital elevation models (DEMs) or triangulated irregular network models (TINs). Generally, DEMs are the preferred surface model format for airborne data due to their computational efficiency and the typical horizontal orientation of most data. However, for near-vertical or overhanging cliffs, DEMs do not model the surface complexity particularly well due to the DEM requirement of one elevation value per grid cell (i.e., vertical cliffs and

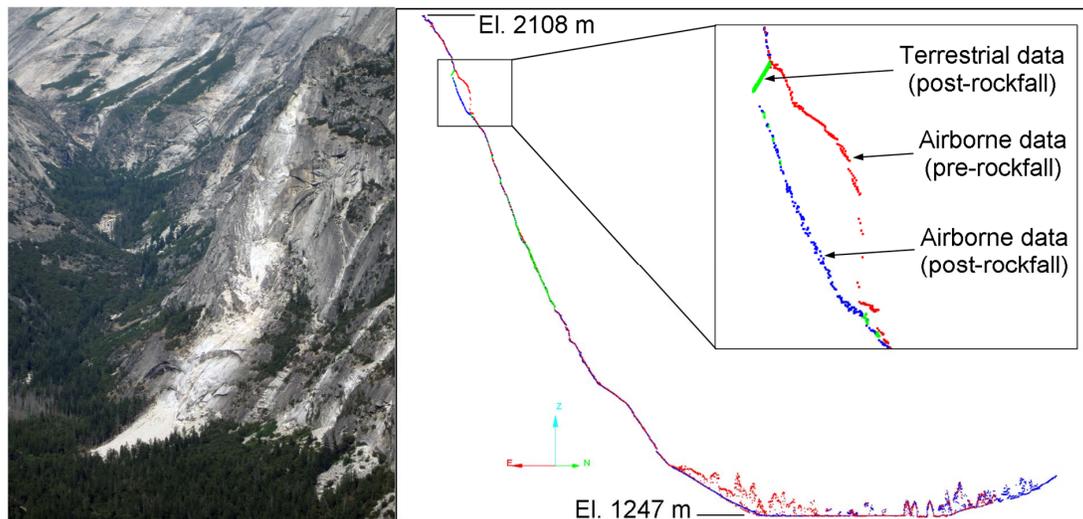


Figure 3. Integrated terrestrial and repeat airborne lidar data from a cliff in Yosemite National Park, California, showing failure of a 25,400 m³ block. Terrestrial data captures downward-facing overhangs, whereas airborne data captures upward facing ledges. By combining the two data sets, all surfaces of complex cliffs can be resolved.

overhangs can not be rendered in a grid-based surface). TIN surfaces are therefore generally recommended and are many times essential for modeling complex cliff topography. With TINs, all points can be used to define a set of triangular facets with any orientation allowed and topology defined by normal vectors to each TIN facet.

Changes in the volume of near-vertical cliff topography calculated with TIN surfaces will be more accurate in almost all cases compared to DEM surfaces. The only exceptions will be in either very regular surfaces (i.e., perfectly planar surfaces) or when a very small cell size (e.g., <10 cm) is used in DEM construction. The only major disadvantages of TIN-based volume calculations are the additional surface complexities inherent in the model and the related computational demand that software algorithms may require. Cross-section generation and interpretation follow the same general guidelines as volume calculations – TIN-based cross-sections are generally more accurate but also more complex. Finally, in all cases, and especially for TIN surfaces, integration of airborne and terrestrial lidar data may be necessary to accurately construct continuous surfaces and cross-sections (e.g. Fig. 3).

Making remote structural measurements of joint and fracture planes

Once a surface model has been constructed from point cloud data, routines for analyzing both overall and specific rock structure can be applied. Quantifying rock structure is important, as rock falls commonly occur in association with joints or other discontinuities (Terzaghi, 1962). Typically, these routines use some form of plane-fitting algorithm to determine the statistical distribution of joint and fracture orientations (e.g., strike and dip), although they may also be used to obtain spacing and planar areas of particular fracture patterns (e.g., joint frequency). The general methodology consists of the following steps, here applied to the measurement of joint planes at Glacier Point in Yosemite National Park, California (Fig. 4):

- (a) Identify a joint plane of interest either in an oblique photograph or lidar data.
- (b) Orientate to an oblique look-angle of the area in the lidar point cloud data.
- (c, d) Isolate points on the joint plane. In the example, 606 points were selected.
- (e, f) Automatically determine the planar best-fit to the isolated points. In the example, the plane fits 586 points with a 16 cm standard deviation.
- (g, h) Calculate the structural geometry. In the example, the measured plane has strike of 355° and dips 31°.

Similar methodologies have also been applied to characterizing rock cut slopes (e.g., Sturzenegger and Stead, 2009). In the example presented here, I-SiTE Studio (2011) software was used on a combined airborne-terrestrial lidar data set. Other programs are also available and include Coltop 3D (e.g., Jaboyedoff et al., 2007; Oppikofer et al., 2009) and Split FX (e.g., Kemeny et al., 2005) which use semi-automated routines to perform these types of analyses. In general, these plane-fitting algorithms are similar to those presented here, but use color-coding or statistical methods to evaluate whether points are on a single plane or on different planes.

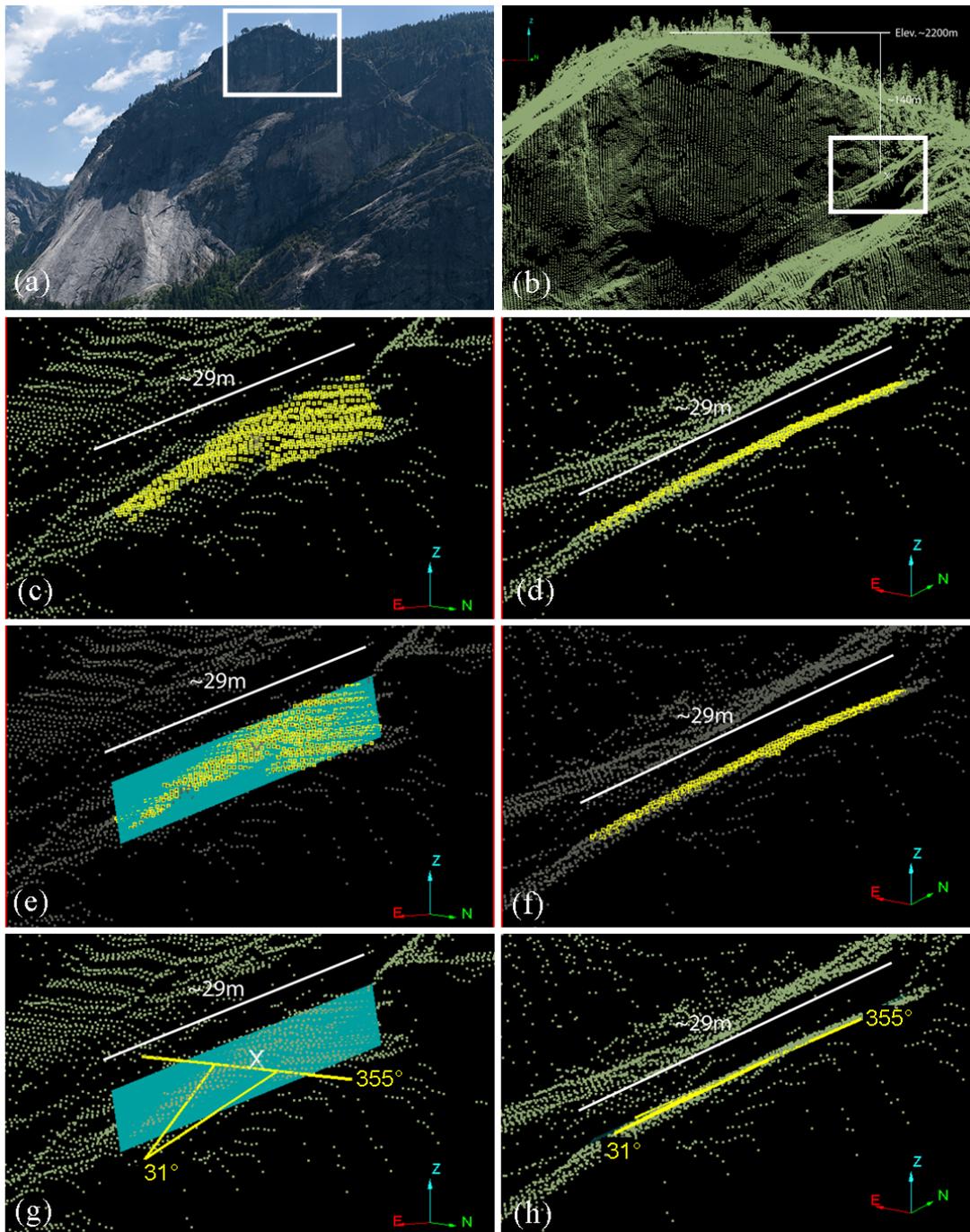


Figure 4. Methodology for making structural (strike and dip) measurements of a joint surface in Yosemite National Park, California. Yellow points delineate data points along the plane of interest, which has a strike of 355° and a dip of 31° . Box in (a) is shown in (b). Box in (b) is shown in (c) through (h). Oblique view pairs from two different orientations are shown in (c-d), (e-f), and (g-h).

Caution must be exercised when using these techniques. Of perhaps greatest importance is the presumption that the point cloud represents the bare-earth surface, that is, that all vegetation or human structures have been filtered out of the point cloud. This can be performed using semi-automated techniques as discussed previously, or evaluated through the use of digital photographs; in general, this is not a great concern when working with steep bedrock slopes and cliffs that typically lack dense vegetation. Of next concern is that the fracture planes visible at the edge of the rock mass represent actual planar surfaces of the internal rock structure being investigated (i.e., joints, fractures, faults, etc.) rather than eroded topographic surfaces or surficial deposits such as soil and talus. If the topography has been eroded, curvilinear point cloud areas may “bend” the results away from the presumed planar orientation of the internal rock mass. This can be avoided by careful comparison of photographs with the point cloud data and by rotating the point cloud data in several different viewing orientations (e.g., Fig. 4c and d) to be sure that selected points are all on the same plane. Ultimately, field ground truthing might be required to fully assess data accuracy.

High-resolution monitoring of surface deformation

When a topographic surface is repeatedly surveyed over time, change detection analyses can be performed. In most cases, this results in volume change calculations and cross-section diagrams showing where net erosion and/or deposition has occurred (i.e., rock fall source areas or talus deposits in cliff settings). When changes occur repeatedly and rapidly over time (e.g., as a result of coastal cliff erosion) and are recorded by repeat lidar scans, complex geomorphologic patterns can be revealed (e.g., Collins and Sitar, 2008). The scale of detectable change will typically depend on the accuracy of the point cloud processing and, when changes are large, the ability to perform change detection is rarely constrained by the methods of registration and georeferencing. However, when surface changes are small, or when the surface does not physically erode but rather deforms, a high degree of survey accuracy must be achieved to detect the changes. This is best performed using a fixed lidar platform in which the laser instrument does not move position between subsequently surveyed data sets (e.g., Gordon and Lichti, 2007).

Collins and Stock (2010) showed that sub-centimeter deformations were measurable at approximately 33 m range using this methodology in a carefully surveyed and monitored rock face that deforms as a result of thermal forcing in Yosemite Valley, California. If the laser position does change, sub-centimeter deformation measurements may still be possible, but registration using nearest-neighbor methodologies may be needed (e.g., Abellán et al., 2009). In general, phase-based scanners with greater accuracy are likely better suited for monitoring sub-centimeter deformations compared with time-of-flight systems used in the previously referenced studies. However, this is only possible if phase-based laser equipment limitations (typically limited range and additional power) are adequate for the site conditions. Unfortunately, this is unlikely for many large cliffs in which rock falls may need to be monitored, thus the techniques referenced herein should be applied with a time-of-flight system.

CONCLUSIONS

Characterization of rock-fall hazards can be logistically difficult due mainly to the relative inaccessibility and hazard of most rock-fall source areas. However, lidar survey methods can be utilized as high-resolution, highly accurate tools to gather the required information needed to make volumetric, structural, and deformation analyses straightforward and potentially routine. Using the techniques presented here, many major pitfalls of lidar-based rock-fall characterization can be avoided. These include ensuring that adequate data point density is obtained during data collection and that structural measurements are properly and rigorously analyzed. With the advent of automated routines integrated into new software programs, applications and analyses should continue to both evolve and become simpler to implement.

ACKNOWLEDGEMENTS

Support for this research was provided by the U.S. Geological Survey and the National Park Service. The post-rockfall lidar dataset in Figure 3 was provided by Valerie Zimmer and Nicholas Sitar. We thank Mark Reid and Skye Corbett of the USGS, and two anonymous reviewers for providing comments on this paper.

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