Title

Computational-Rock Mechanics in Pedagogy and Practice

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Computational-Rock Mechanics in Pedagogy and Practice

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ABSTRACT: Point cloud modeling of rock slopes using LIDAR and Structure-from-Motion digital stereophotogrammetry provides, at a minimum, thousands of facets and facet normals that can be used to identify the densities of orientations of rock mass discontinuities, the geometries of potentially removable blocks, and the character of the excavation face. As part of the Engineering Geology graduate curriculum at the Civil and Environmental Engineering program at the University of California, Berkeley we teach graduate students an integrated methodology for [a] gathering point cloud information be laser or camera; [b] computing facets and facet normals form point clouds for stereonet presentation and geometric analysis of block dimension; [c] extract rock mass discontinuities from stereonet data to analyze key blocks, assess discontinuous deformation analysis (DDA) behavior, and model rock slope stability. These new methods require a suite of different software tools discussed in the paper to move through the workflow process. Computational rock mechanics provides data sets that are orders of magnitude richer in detail and result in better understanding of rock slope and tunnel key block behavior. Full application of computational rock mechanics methods should reduce the cost of bolting by identifying critical support orientations and design loads.

1 .INTRODUCTION

This paper is intended to serve as an instruction manual for teachers who include digital methods in rock mechanics. Innovations in digital methods for computing surface models have advanced such that models can be used for quantitative rock mechanics analyses. An array of new remote sensing tools utilizes laser and photogrammetric means to build digital twins of a surface at millimeter-to-centimeter accuracy by processing a point cloud of the target. The oldest of these technologies, Terrestrial Laser Scanning (TLS), has transformed the ability of engineers to document geotechnical sites.

Though TLS remains an expensive technique for capturing point clouds of data needed to model surfaces, the cost has dropped in the last decade, and is now widely available on common cell phones. A remarkable new computer vision-based method, Structure-from-Motion (SfM), allows engineers to build complex pointcloud visualizations with digital cameras (airborne or handheld) at a fraction of the cost. In the sections below, we outline a procedure for gathering data and moving through the analysis process to extract meaningful rock mechanics information from point cloud data. The procedural steps are outlined in Figure 1.

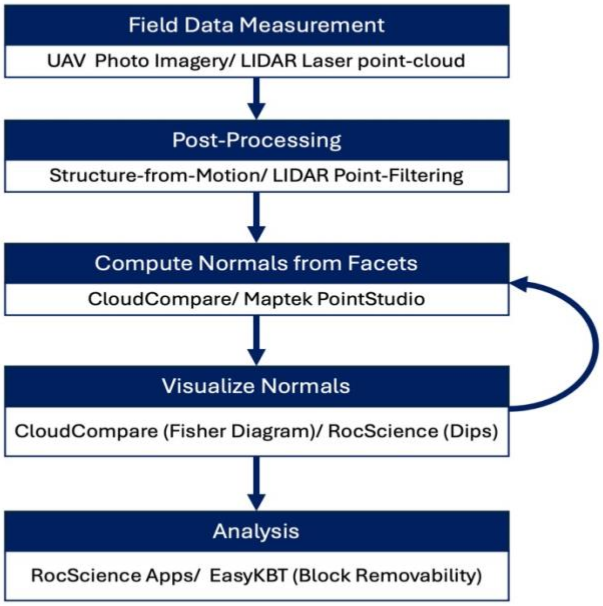


Figure 1. Flow Chart of digital procedures from point cloud to rock mass kinematics and removability studies.

2.A PROCEDURE FOR COMPUTATIONAL ROCK MECHANICS

Step 1:Making Point Cloud Measurements

At the University of California, Berkeley, the authors teach a graduate-program course on Engineering Geology.

One of the principal improvements to the curriculum is to fully incorporate a digital point cloud analysis into lectures and assignments. Point clouds are collections of individual points that are characterized by azimuthal and Zenith angles, range, signal attenuation, and typical RGB intensity values. Post-processing conversion to Cartesian coordinate spatial values - Northing, Easting, and Elevation - is needed to merge and register multiple data sets. A point cloud is a collection of individual measurements that together model the surface geometry of a landscape. There are many ways of collecting point clouds, which vary in the accuracy, complexity of the work, and the cost of equipment. The authors use two approaches for collecting point clouds in the course: terrestrial laser scanning (TLS) and processing photogrammetric models with Structure-from-Motion from static images collected by an unmanned aerial system (UAS). The TLS laser scanning traditionally delivers higher accuracy for the models, whereas SfM offers more flexibility, a top down view of the target study area, and requires less labor and access to the target.

Near-infrared TLS- laser sensors are employed in our topographic studies because they are eye-safe at low power levels and the standard lasing crystal is inexpensive to manufacture. As such, near-infrared lasers are the most common type of Light Detection and Ranging (LIDAR) tool. Terrestrial laser scanning typically involves the deployment of 1064-nm YAG-laser instrumentation that images structures and ground and records three-dimensional positions and beam attenuation. The TLS method produces point-cloud position datasets which contain clusters of millions or billions of individual position measurements. Modern TLS field deployments are from fixed locations or moving vehicular platforms while airborne systems can be mounted to UAS- systems or piloted aircrafts. The point cloud or meshed surface models document the geometric state of the structures at the time of capture and can be used for change detection of volumes, areas, and distances.

'Structure-from-Motion', the modern digital form of topographic analysis from stereo-photogrammetry, uses large groups of overlapping images and pixel recognition software. Any high-resolution digital camera with a fixed lens can be used for SfM. UAV-based platforms are especially useful for capturing optimal imagery of a project site from multiple elevations and orientations (Figure 2). To build a topographic model from overlapping imagery, common tie-points (sparse pixel groups) are found in adjacent images. The GPS location coordinates of the camera along with lens properties are used to determine the angular geometry between common pixels in the scene and the moving camera positions. Four matrices are computed to adjust pixel locations and model scaling for projection-, affine parallelism-, similarity-, and Euclidean-scaling. Ground reference targets can be used to assist the Euclidean matrix calculation. Finally, a dense point cloud is computed based on the correction factors modeled in the matrix calculations. Using best practices, the point cloud accuracy can be at the centimeter or even millimeter scale.

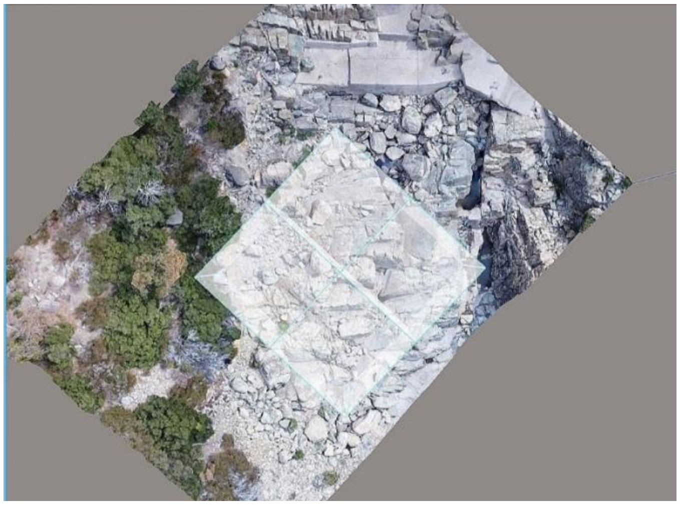


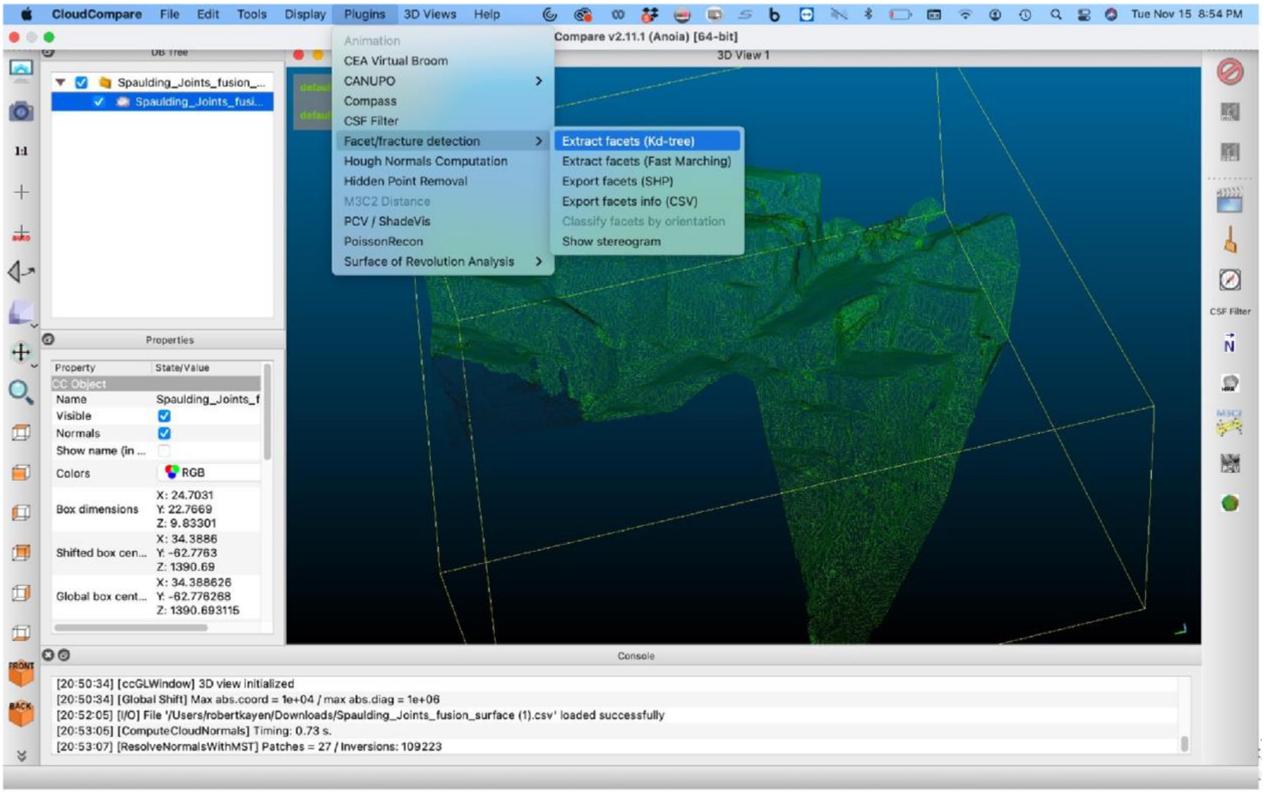
Figure 2. UAV orthomosaic of SfM data and specific tiles of point cloud data selected for study at Auxiliary Dam #2, Spaulding Dam, California. The point cloud tiles have photo-based RGB color and were processed in Bentley iTwin software.

The shortcomings of SfM modeling include an inability to penetrate vegetation to model the bare earth, distortions that can occur from overhanging terrain, non-static objects such as vegetation in the wind, poor photo quality due to weather conditions, and warping along the outer margins of the models. Some SfM point-cloud processing algorithms struggle to model sharp transitions from horizontal to vertical terrain that occurs at the base of structures.

Step 2: Preparing Point Cloud Data For Rock Mechanics Studies

The processed point cloud is the starting point for analyzing rock mass discontinuities. Registration and filtering are needed to build a project-level point cloud from multiple scans or hundreds of photographs. To identify discontinuities in the rock mass, point clouds associated with vegetation need to be removed. One of the powerful aspects of LIDAR laser scanning is the ability to easily eliminate vegetation using software filters. The narrow columnated laser pulse of the TLS instrument can penetrate through partial vegetation cover and strike the ground. A shortcoming of the SfM photogrammetric method is an inability to penetrate vegetation to model the bare Earth, such that a clear view of the rock mass is needed.

The individual measurements of a point cloud can be connected to their neighboring points with a "Triangular-Irregular-Network" or TIN. A typical point cloud survey can result in thousands or millions of connected triangles. Each triangle of the TIN has an orientation that can be modeled as a dip and dipdirection, with a corresponding normal pole-vector (Figure 3).



Property	State/Value
CC Object	
Name	Spaulding_Joints_f
Visible	☑
Normals	☑
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Colors	RGB
Box dimensions	X: 24.7031 Y: 22.7669 Z: 9.83301
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Global box cent...	X: 34.388626 Y: -62.776268 Z: 1390.693115

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[20:53:05] [ComputeCloudNormals] Timing: 0.73 s.
[20:53:07] [ResolveNormalsWithMST] Patches = 27 / Inversions: 109223
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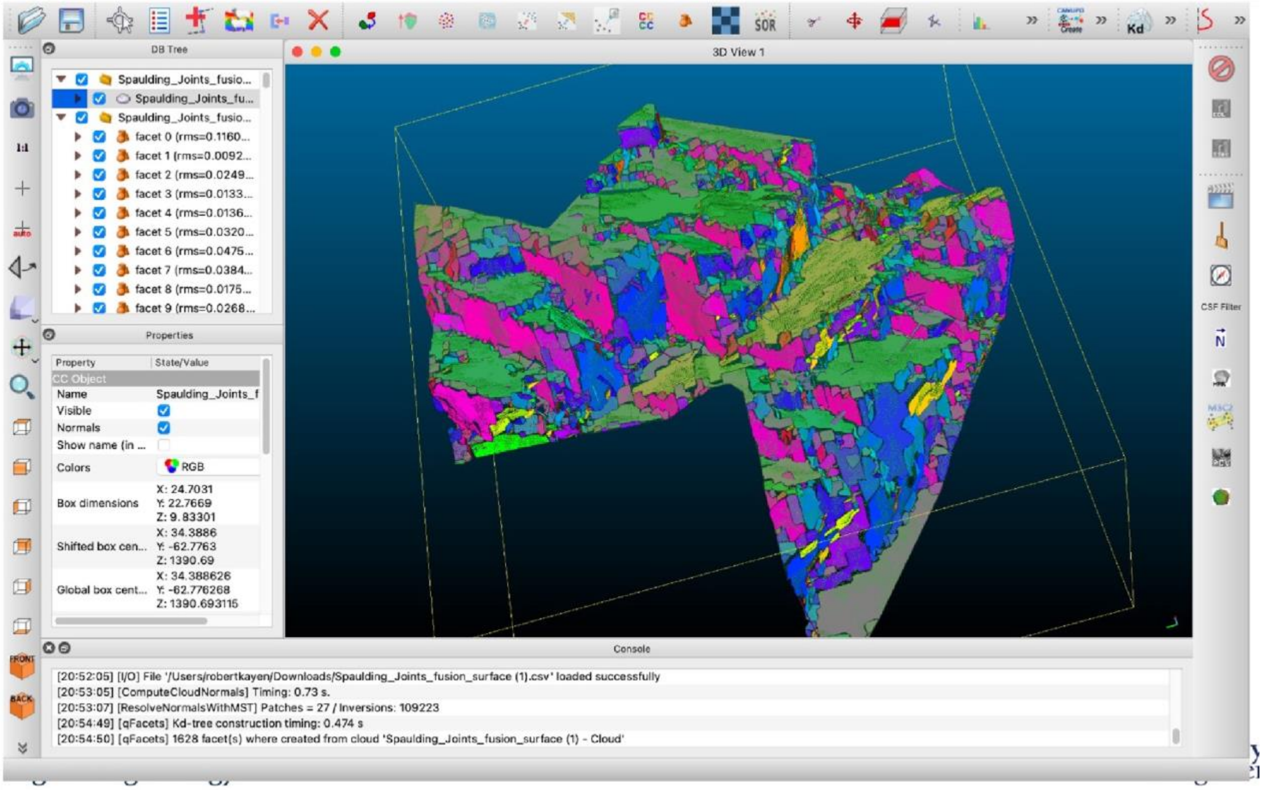
Figure 3. Computing TIN normals in CloudCompare for use in stereonet modeling

Many programs are available for modeling point clouds, filtering out vegetation and transient objects, as well as modeling TIN surfaces. In our Engineering Geology Course, the authors use software that is provided by vendors who support free academic licensing. The programs that are taught include *Bentley 'iTwin'* for modeling SfM data, *Maptek 'PointStudio'* for TLS LIDAR data, *'CloudCompare'* for facet development and stereonet analysis, and *Rocscience 'Dips'* for stereonet analysis.

Step 3:Computation Of Facet Normals For Pole-Method Stereonet Analysis

Facet normals are the basis for rock mechanics modeling. Their clustering associated with rock mass joints and discontinuities can be identified through a stereonet analysis. Partial vegetation cover of a site will produce randomly distributed facets and pole-normals. These random poles increase the data "noise" in the stereonet and dilutes the signal of the discontinuity orientations. Practitioners need to clear points associated with vegetation to best extract the joint characteristics. To model the TIN facets, it may be useful to down-sample the point cloud to a minimum point separation that allows for identification of the discontinuities but limits the number of facets. All point cloud programs allow for down-sampling of points. Alternatively, the number of facets of a surface model can be 'simplified' by creating larger averaged facets from many smaller facets.

To analyze orientations, the TIN is processed to determine the 'Pole' of each facet and *CloudCompare* can be used for this process. This is done by converting a point cloud into triangles and normals using the 'Compute Normals' in the edit menu (Figure 4). Oriented facets can be visualized using a plug-in developed by Thomas Dewez, BRGM, and his colleagues (2016) called the 'BRGM Fracture detection plugin'.



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☑ facet 6 (rms=0.0475...
☑ facet 7 (rms=0.0384...
☑ facet 8 (rms=0.0175...
☑ facet 9 (rms=0.0268...

Property	State/Value
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Name	Spaulding_Joints_f
Visible	☑
Normals	☑
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Colors	RGB
Box dimensions	X: 24.7031 Y: 22.7669 Z: 9.83301
Shifted box cen...	X: 34.3886 Y: -62.7763 Z: 1390.69
Global box cent...	X: 34.388626 Y: -62.776268 Z: 1390.693115

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[20:52:05] [I/O] File '/Users/robertkayen/Downloads/Spaulding_Joints_fusion_surface (1).csv' loaded successfully
[20:53:05] [ComputeCloudNormals] Timing: 0.73 s.
[20:53:07] [ResolveNormalsWithMST] Patches = 27 / Inversions: 109223
[20:54:49] [qFacets] Kd-tree construction timing: 0.474 s
[20:54:50] [qFacets] 1628 facet(s) where created from cloud 'Spaulding_Joints_fusion_surface (1) - Cloud'
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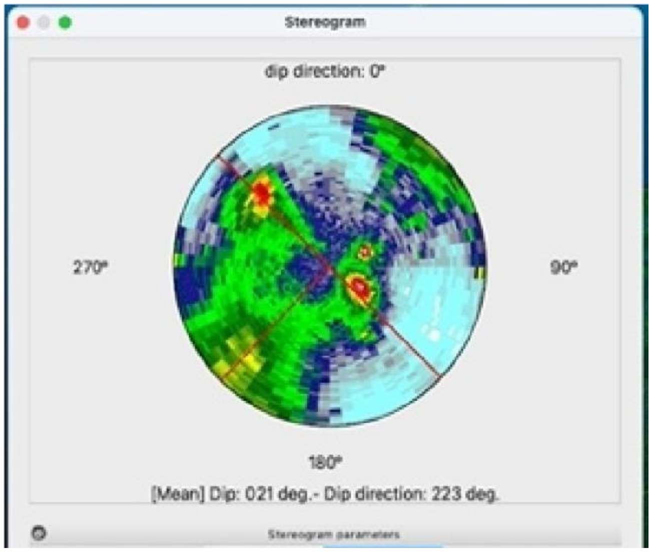
Figure 4. Dip-direction and dip angle-colored facets in *CloudCompare* derived from Bentley iTwin a point cloud.

Exported facets can also be analyzed using *RocScienc*e

The number of facets (groupings of triangles) and their complexity can be modeled using an adjustable minimum number of points and maximum length dimension. An example of color-oriented facets can be seen in Figure 4.



[Mean] Dip: 021 deg.- Dip direction: 223 deg.

Figure 5.Upper hemisphere projection of upward directed poles in the Stereonet feature of *CloudCompare* from several hundred thousand TIN triangle normals. software *Dips*. It is a useful exercise to export the dip and dip-direction data from *CloudCompare* and input these data into *RocScience Dips*. The program *Dips* allows for control of either upper or lower hemisphere projection, and the upward or downward directed poles.

Step 4:Extracting Digital Discontinuities For Kinematics And Key Block Theory

The digital stereonet diagrams (Figure 5) are useful for estimating the mean values and distributions of joint orientations in terms of dip and dip-direction. These can be used to assess wedge failure in a probabilistic manner. In the *RocScience* program *sWedge*, friction estimates of the joint sets can be used to evaluate the distributions of the factor of safety associated with orientation distributions to assess probability of failure.

Easy KBT allows students to enter the joint sets determined from *DIPS* or *CloudCompare* and their spacing. The program computes the geometries of finite blocks above and below the various joint planes and identifies those blocks whose geometries and orientations are likely to collapse into an excavated underground chamber. The user can define the geometry and size of the underground space or tunnel to assess key blocks. This exercise allows students to see not only roof blocks but dangerous key blocks that can fall into

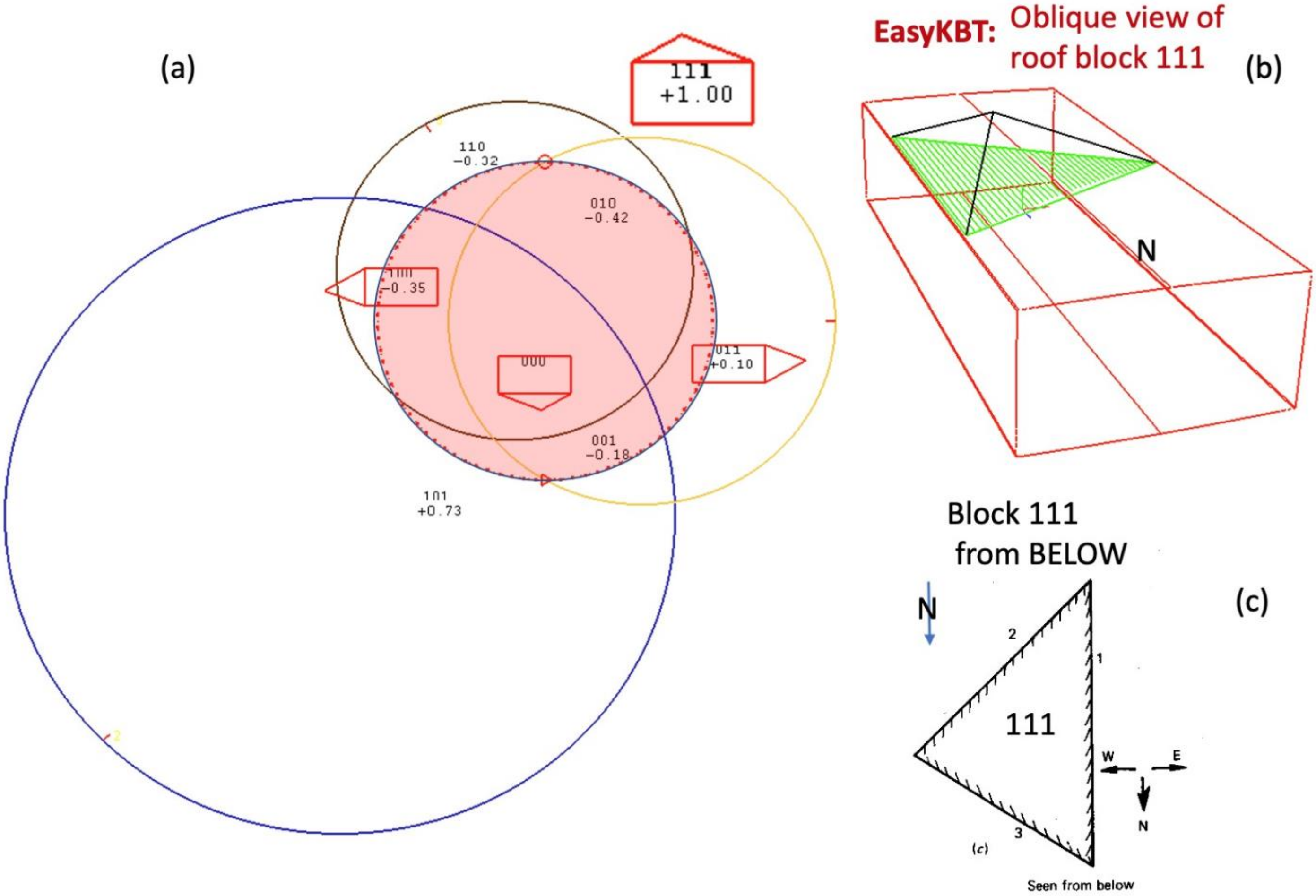


Figure 6. Joint sets are used to compute key blocks (e.g. block '111') in *EasyKBT* software that can fall from the roof into an underground excavation. On the left (a) is a full sphere stereonet, and on the right is an oblique view (b) and upward looking view (c) of key roof block 111. Figure 6.c is from Goodman, (1991) *Introduction to Rock Mechanics.*

underground excavations from the side walls (Figure 6). The tool used is EasyKBT (Easy Key Block Theory) Students are tasked with exploring computational block theory concepts developed by Richard Goodman and Dr. Genhua Shi at Berkeley. and programmed by the Engineering Computer Center, University of the Chinese Academy of Sciences in 2014.

While not taught in the Engineering Geology course at Berkeley, the computed joint orientations from the SfM methodology can also be applied to the discontinuous deformation analysis (EasyDDA) software from Genhua Shi and the University of the Chinese Academy of Sciences to understand discontinuous rock mass behavior.

3.DISCUSSION

Traditional stereonet analyses require manual field measurements of dip and dip-directions collected on all discontinuities present in the rock. Manually collecting field data introduces bias into measurements. Humans typically will measure joint orientations that are easy to obtain in the field, either due to a preferred orientation of the joint set or due to ease of access to a rock outcrop. Major joint orientations are also more likely to be measured than minor joint orientations as they are more visible, occur more frequently, and are typically easier to access (Figure 7).

Using the computed joint orientations from SfM removes human bias from measurements. Due to the hundreds of thousands of normals, the natural variation in the discontinuities can be measured throughout the entirety of the outcrop, for all major and minor discontinuities. This methodology also removes the bias related to measuring preferred orientations. UAVs increase the feasibility of collecting data for rock outcrops that are in challenging locations and will image all visible discontinuities in the rock mass, creating a more accurate representation of the stability of the system.

The effect of human bias on the collection of orientations in a stereonet analysis is shown in Figure 8. Data shown for both the manual- and digital-stereonet were collected at Spaulding Dam Spillway, located in Nevada County, California. The stereonet showing the manual field data collection is composed of approximately 180 measurements collected by 20 students during a one-hour period. The stereonet showing the computed orientations from SfM shows hundreds of thousands of measurements for the same location.

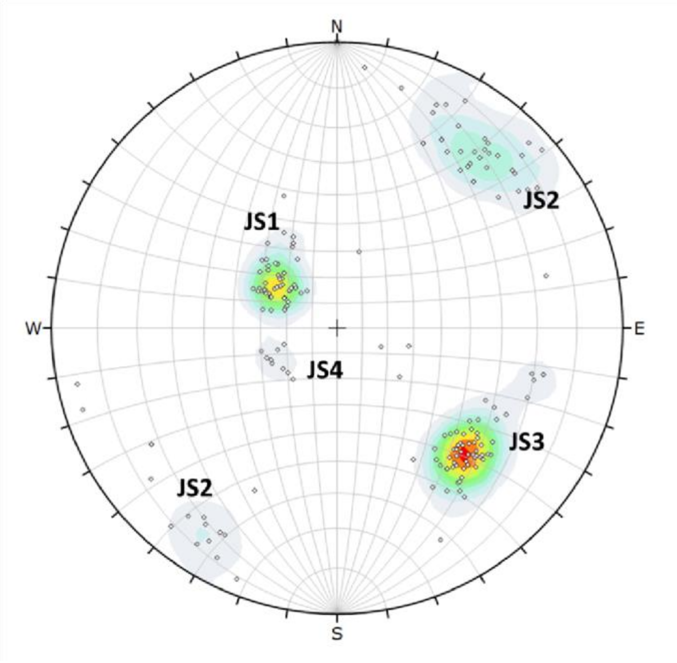


Figure 7. Field class of CE281 gathered 180 orientation values measured by hand (note manual stereonet plots are lower hemisphere downward-directed poles).

The manual stereonet uses the conventional method of plotting downward directed poles to represent the joint orientations. The normals to the orientation of the joint sets are represented as poles on the stereonet, illustrated by points. The contouring shows the density distribution of the facet-poles. The manual stereonet collected by the students shows three distinct clusters of joint sets (Joint Set 1, 2, and 3) and one minor joint set (Joint Set 4). The data for these joint sets is summarized in Table 1.

The three major joint sets were characterized well by the students with 31% of the overall measurements taken for Joint Set 1, 22% of the overall measurements taken for Joint Set 2, 35% of the overall measurements taken for Joint Set 3, and only 11% of the overall measurements were taken for Joint Set 4. Due to the optimal orientations of Joint Set 1 and Joint Set 3, students were more likely to take measurements as they were easily visible and at a desired orientation for taking measurements. Joint Set 3, which was much steeper than the other joint sets, was more difficult to take measurements of, resulting in less data points. Since Joint Set 4 was a minor joint set at the site, few students were able to recognize this discontinuity, resulting in it not being fully characterized by the majority of students.

Because Joint Sets 1, 2, and 3 were the major joint sets at the site, they were easily visible and accessible for manual data collection. The manual stereonet shows little variation for Joint Set 1 and Joint Set 2. Joint Set 1 and 2 both had low standard deviations of 05° to 06° in dip and 021° to 024° in dip-direction. In comparison, Joint Set 4, the minor joint set at the site, had a large standard deviation in dip at 25° indicating that there was high variability in the data.

Table 1. Measured Joint Orientation collected manually

JS	**Mean Dip (°)**	**Standard Deviation Dip (°)**	**Mean Dipdirection (°)**	**Standard Deviation Dip-direction (°)**
1	30	06	124	021
2	77	05	224	024
3	63	09	306	042
4	68	25	045	016

The digital stereonet shows the same four joint sets but flipped due to the unconventional upwards directed poles. In lieu of how the digital stereonet visually represent the data, the digital and manual stereonet show the same information. The digital stereonet shows the density distribution of the normals to the joint orientations. The

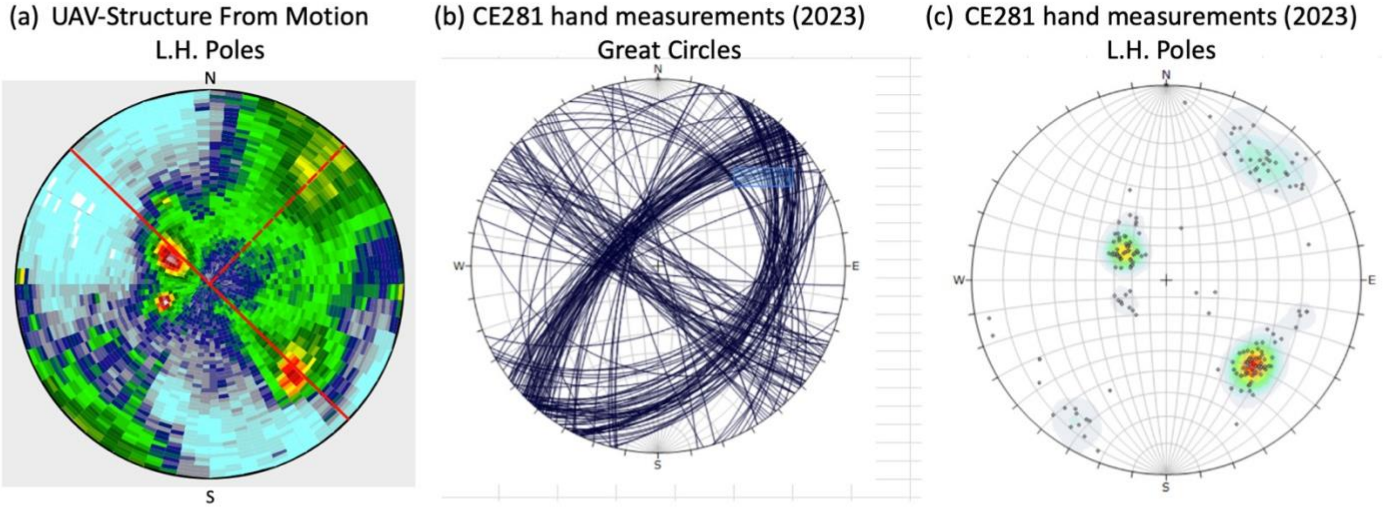


Figure 8. (a) Several hundred thousand upper hemisphere, upward directed poles from *CloudCompare* contrasted against approximately 180 values (b & c) measured by students manually over one hour (note all stereonet plots are

locations with reds and oranges represent high density of normals and areas that are blue represent low density of normals

Joint Set 1, Joint Set 3, and Joint Set 4 have a dense distribution or normals, shown by the red coloring while Joint Set 2 had less of distribution because UAV collected data does not contain location or visibility bias, unlike humans. Joint Set 4 is more accurately measured and characterized compared to the manual stereonet. In this analysis, thousands of normals were collected for Joint Set 4 in comparison to the 11% of the data collected by the students. The effect of human bias is also shown in the variability of the data. In the digital stereonet, the variability is accounted for and is shown by the density distribution throughout the entire stereonet. The manual stereonet shows significantly fewer areas with pole density.

4. CONCLUSIONS

In this paper, the authors have outlined a suite of procedures that allow students and practitioners to gather point cloud data, process it within convention hemisphere and key-block full sphere stereonet models, and use the results to assess kinematic stability and block removability. Many new applications are being developed for building and analyzing point clouds and TIN's, and as such, the software listed in this paper is only intended to be representative of what is possible for use in this domain. Nevertheless, it is possible to scan and model an exposed outcrop and move entirely though an analysis to assess complex problems of block removability without any physical contact with the rock mass. Likewise, with the addition of laboratory measurements or literature estimates of joint friction, a non-destructive and non-invasive analysis can be made of block kinematics and stability.
lower hemisphere downward-directed poles).

The use of point clouds to assess problems in rock mechanics creates enormous sets of joint-related poles often in the thousands-to-hundreds of thousands. The number of poles we evaluate has exceeded the maximum number of poles several rock mechanics software packages allow, and thus requiring surface modeling simplification to make the large data sets useable. The Fisher diagrams and pole statistics are particularly useful products of the digital method for rock slope stability analyses.

Finally, through practice we have learned that computational rock mechanics using TIN facet poles eliminates human bias in selective orientation measurements and leads to better characterization of problems.

5. ACKNOWLEDGEMENTS

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