APPLICATION OF DIGITAL PHOTOGRAMMETRY TO ROCK CUT SLOPE DESIGN

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ABSTRACT

To reduce future maintenance along a rockfall-prone stretch of U.S. Highway 15 on Bald Eagle Mountain near South Williamsport, the Pennsylvania Department of Transportation proposed to remove an existing rockfall fence and modify the existing cut to provide a rock catchment ditch in order to mitigate the rockfall hazard.

Digital photographs were used to develop a three-dimensional, digital model encompassing a 420-foot-long section of the existing rock cut. The orientations of 238 rock discontinuities visible in the model were measured. A Brunton Geotransit was used to collect additional measurements from behind the rockfall fence and to validate the model measurements.

Discontinuity measurements were used to analyze the potential for plane, toppling, and wedge failures, to assess the variability of dip angle and dip direction along the alignment, and to optimize the azimuth of horizontal drain holes. The digital model was used to locate the possible outcrop of clay seams encountered in rock core borings.

Using digital photogrammetry permitted measurement of discontinuities in higher parts of the outcrop without rappelling or free-climbing. A great volume of data was collected in a short period of time, reducing exposure to rockfalls and traffic. Discontinuities were measured over a greater area of their extent, and discontinuities having limited surface exposure were measured by digitizing their trace across the outcrop. Using digital photogrammetry reduced the potential for human error in the collection, recording, and processing of data, and facilitated performance of some of the analyses required for designing a safer rock cut slope.

INTRODUCTION

Rockfalls have been a recurring problem on a curved portion of U.S. Highway 15 on Bald Eagle Mountain south of Williamsport, Pennsylvania. Conditions contributing to rockfalls include bedding planes dipping obliquely toward the roadway, joints dipping steeply into the cut providing an upper release surface, steeply dipping orthogonal joints providing lateral release surfaces, and undercutting of quartzite beds as a result of differential weathering of weaker shale and siltstone beds (Figure 1).

Rockfalls typically occur during the late winter and early spring, when during peak freeze/thaw conditions, rockfalls may occur nearly daily or several times a week over the period of a month. Fallen rock blocks are estimated to be up to about 0.5 yard^3 (0.4 meter^3) in size and often require a loader to move, which necessitates a lane closure. To reduce future maintenance and improve safety, the Pennsylvania Department of Transportation (PennDOT) proposed to remove an existing rockfall fence, modify the existing rock cut, and provide a rockfall catchment zone. Modification of the rock cut will also improve sight distance.

Rock discontinuity data were needed to perform the rock slope stability analyses required for developing revised cut slope recommendations. A Brunton or clar compass is typically used to measure rock discontinuities; however, collecting measurements can be perilous work in areas of challenging access, areas of instability, and areas of high traffic volume. Digital

FIGURE 1 Bedding, jointing, and differential weathering in existing rock cut.

photogrammetry was successfully used to collect the rock discontinuity data. This paper summarizes the site geology, describes the process used to obtain the discontinuity data, explains how the discontinuity data and digital terrain model were used, and discusses some of the advantages of using digital photogrammetry for rock cut slope design.

PROJECT LOCATION

The project is located on Bald Eagle Mountain, south of Williamsport, Pennsylvania. Bald Eagle Mountain forms the northern tip of the Appalachian Mountain Section of Pennsylvania's Ridge and Valley Province *(2)*. The strata underlying Bald Eagle Mountain are tightly folded into an anticline plunging to the east and breached to the west. The project is situated in Wind Gap, which is the first gap west of the nose of the anticline (Figure 2). The project is located at the north end of Wind Gap where Highway 15 curves sharply to the west and descends to its

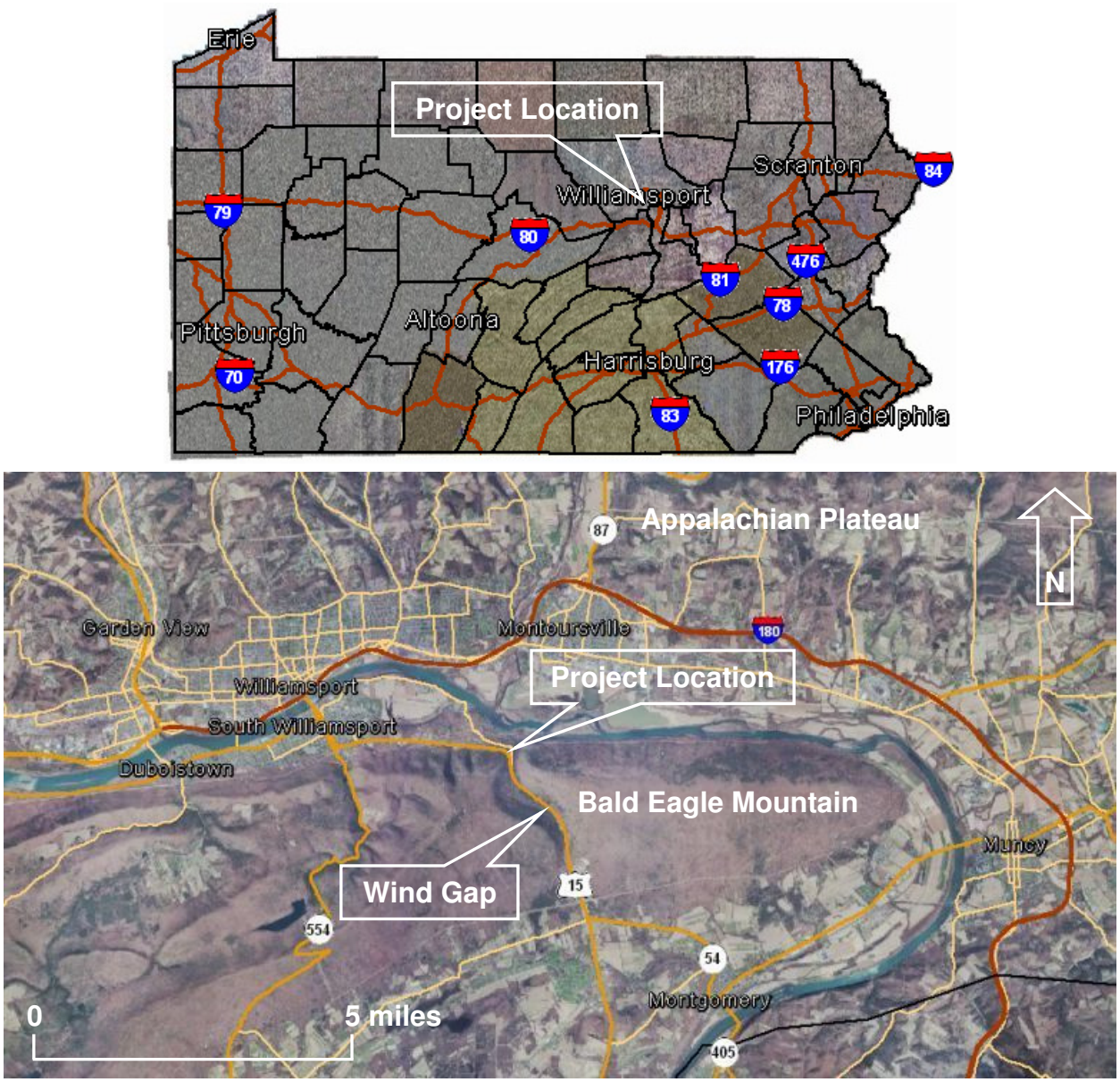

FIGURE 2 Project location *(1)*.

crossing of the Susquehanna River to the north. The project location provides a remarkable vista of the Susquehanna River Valley and the Appalachian Plateau to the north, and PennDOT has developed a scenic overlook, with parking and picnic tables, for highway travelers to enjoy the view.

PROJECT GEOLOGY

According to mapping published by the Pennsylvania Geological Survey *(3)*, the project is situated between the axial trace of the Nittany anticline to the south and the Sylvan Dell syncline to the north (Figure 3). The project straddles the contact between the Juniata Formation of the Upper Ordovician system to the south and the Tuscarora Formation of the Lower Silurian system to the north *(3)*. According to Faill *(4)*, these rocks formed from sediments deposited in the

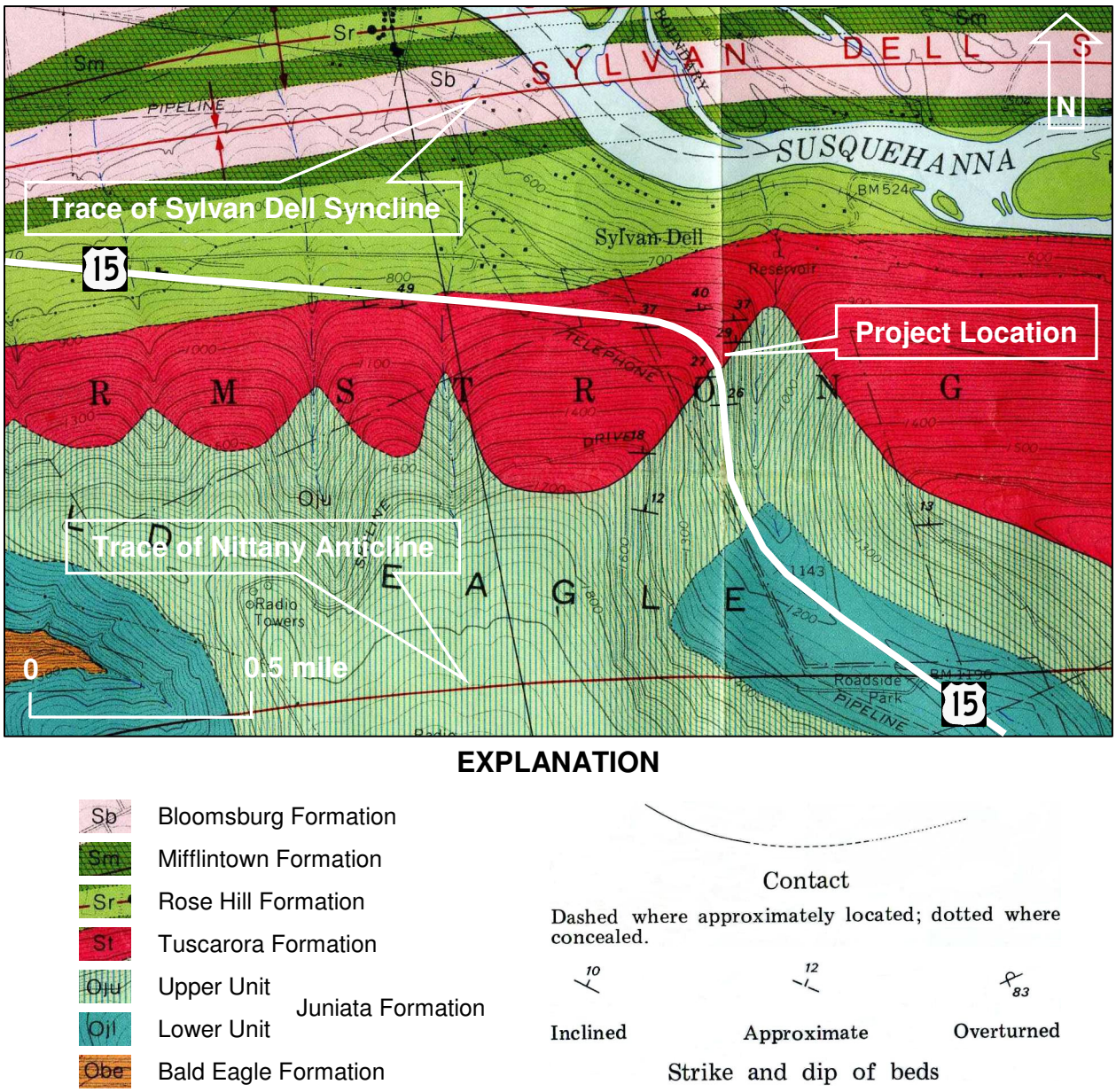

FIGURE 3 Project geology *(3)*.

Appalachian basin from a source area (the Taconic highlands) located to the southeast of the basin. The rocks generally consist of fine- to coarse-grained quartzite interbedded with very fine and fine-grained sandstone, siltstone, and shaly siltstone. The geologic mapping indicates that in the vicinity of the project, the bedrock strata dip approximately 26 to 37 degrees to the north. The area above the existing cut is State Forest Land and mantled with colluvium.

DIGITAL PHOTOGRAMMETRY

Photogrammetry is the practice of determining the geometric properties of objects from photographic images. Stereophotogrammetry uses photos taken from different locations to determine an object's coordinates. The technique takes advantage of the fact that sight rays from an object strike different parts of a camera's image sensor as the location of the camera changes. Knowing the camera's focal length, the shift in sight rays can be used to triangulate an object's location. The advent of digital cameras and high-speed computers combined with the development of sophisticated software has led to the application of digital photogrammetry to rock face characterization *(5, 6, 7)*.

An initial site reconnaissance indicated that the most significant portion of the existing rock cut could be photographed from a grassy area adjacent to the parking lot of the scenic overlook. Because of the existing steep slope, challenging access, and high traffic volume, digital photogrammetry was selected as the method of choice for obtaining the bulk of the rock discontinuity orientation data required for the cut slope design.

Characterizing a rock face using digital photogrammetry involves the following steps:

1. Calibrate camera/lens
2. Plan photo shoot
3. Place survey control points
4. Take photographs
5. Match common points – solve free network orientation
6. Digitize control points – solve absolute orientation
7. Generate digital terrain model (DTM)
8. Define features and perform analyses

Calibrate Camera/Lens

Camera and lens calibration parameters include focal length, radial lens distortion, principal point offsets, decentring distortion, and pixel scaling factors. Calibration is typically done once for each camera and lens combination, and re-calibration between projects is not necessary. A previously calibrated Canon EOS 5D Mark II digital camera with a 50-mm long lens was used for this project.

Plan Photo Shoot

The photo shoot is planned based on the type of photogrammetry model to be developed. Three types of models are typically used in terrestrial photogrammetry:

1. Simple Convergent Model: Photograph the area or object from two camera locations to create a stereo pair of images.
2. Image Fan Model: Multiple photographs are taken obliquely from two locations, usually with a long focal length lens.
3. Image Strip Model: Photographs taken head on from multiple locations, usually with a wide angle lens.

Site topography restricted the distance from which the rock face could be photographed (i.e., the object distance), so an image strip appeared to be the most feasible model in this case. This model usually requires 60 percent horizontal overlap of the images; however, the amount of overlap was slightly increased due to the curving nature of the alignment. The plan also sought to keep the object distance the same for each camera location (approximately 50 meters). Based on the anticipated object distance, a plan for shooting the rock face with a 50-mm lens from nine locations was developed (Figure 4).

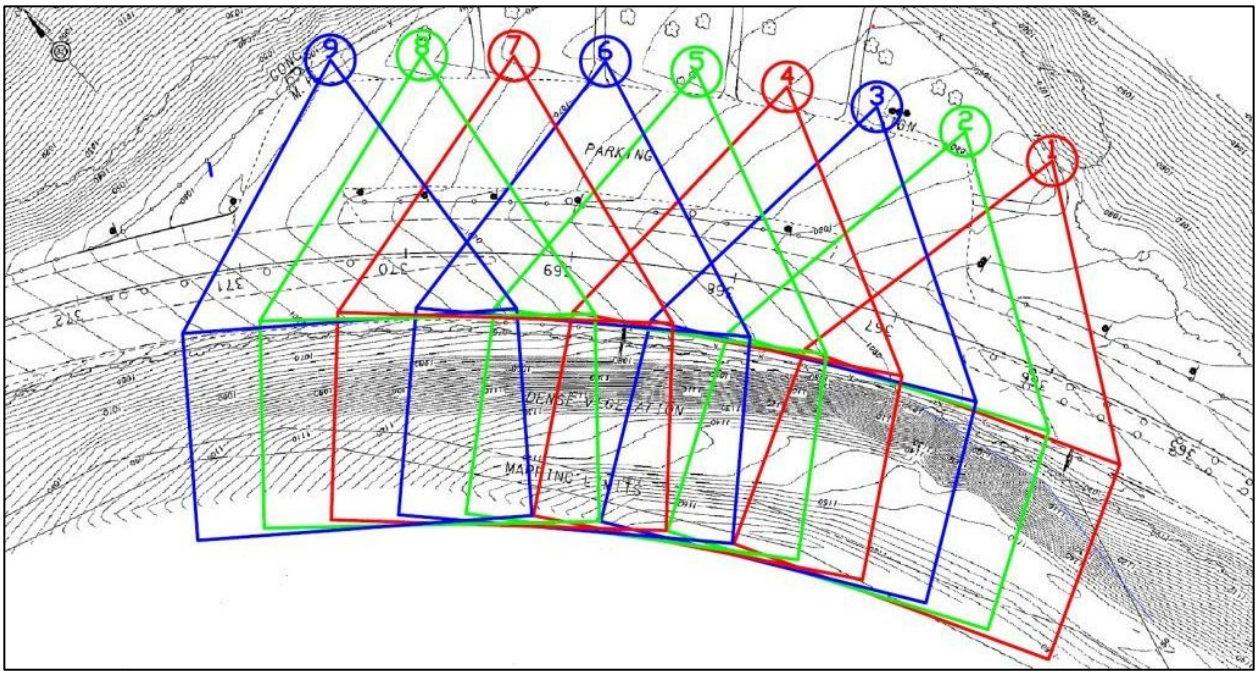

FIGURE 4 Plan for shooting image strip model.

Place Survey Control Points

Prior to taking the photographs, twenty-two 6-inch-diameter control points were spray-painted and labeled at various locations on the cut and the existing rockfall fence. PennDOT surveyors provided the Northing, Easting, and elevation of each spray-painted control point. Although only three control points are required to register the model to a real world coordinate system, using more than three control points provides redundancy, which is useful for estimating the accuracy of the model and insuring against bad observations.

Take Photographs

Photographs were taken on the afternoon November 19, 2010. A tripod was used to steady the camera, and a remote switch was used to activate the shutter and minimize movement of the camera (Figure 5).

Match Common Points – Solve Relative Orientation

Photogrammetry software (3DM Analyst Lite Suite) developed by Adam Technology was used to develop the three-dimensional digital model. Common points were identified in pairs of overlapping photos, and a bundle adjustment was performed to determine the relative camera locations.

FIGURE 5 Photographing the rock face.

Digitize Control Points – Solve Absolute Orientation

After the free network orientation was solved, surveyed control points were digitized, and an absolute orientation was solved to tie the model to a real world coordinate system. Figure 6 illustrates the plotted locations of the camera stations (purple icons), the matched points (red dots), the surveyed control points (teal dots), and the coordinate axes—northing, easting, and elevation.

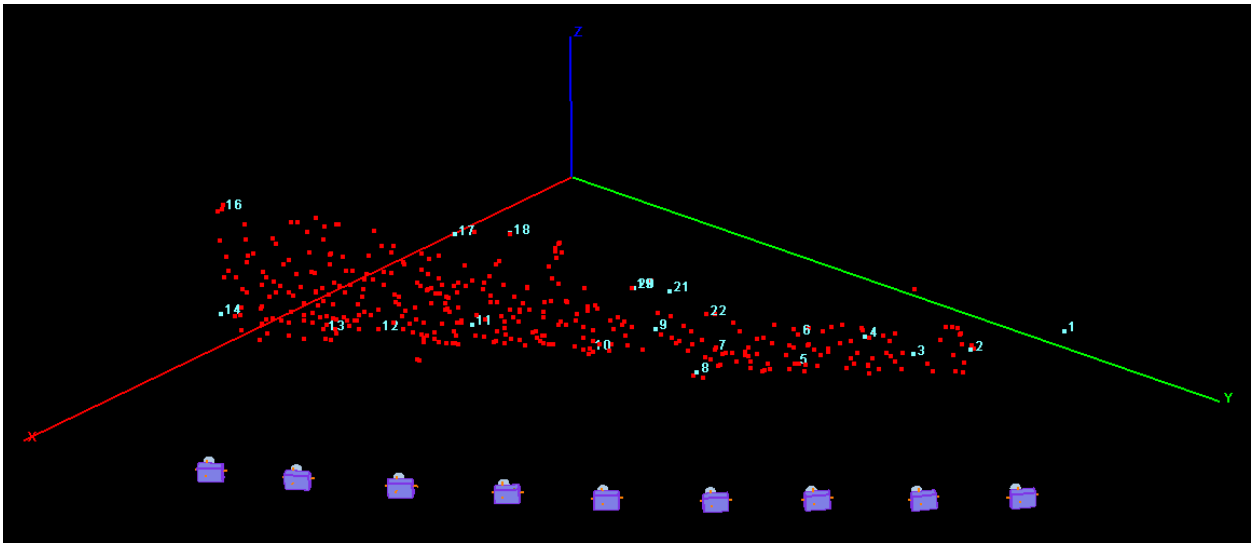

FIGURE 6 Orientation of nine camera stations, matched points, and control points.

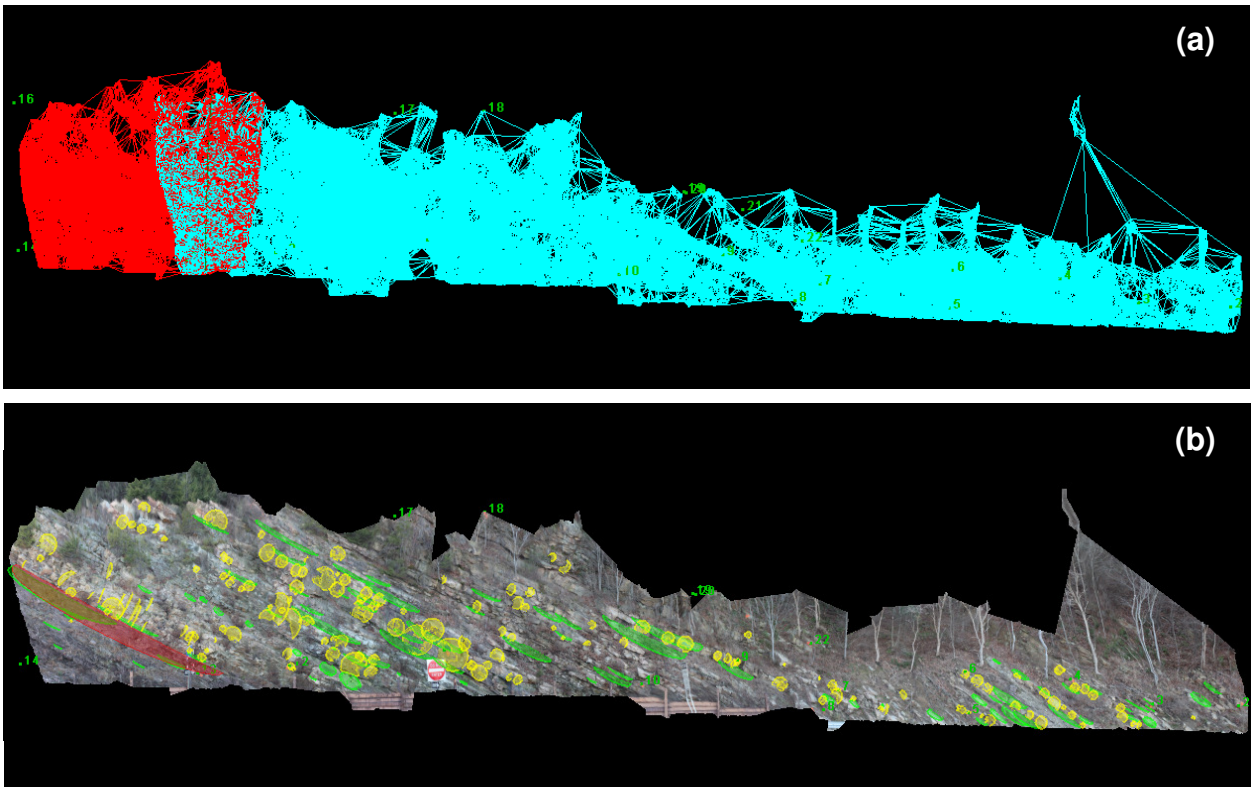

FIGURE 7 Screen captures showing (a) digital terrain model (DTM) of approximately 420 feet of existing rock cut, and (b) digital image model after feature picking.

Generate DTM

Following the bundle adjustment, a digital terrain model was generated based on the matched points and other common points recognized by the software program (Figure 7a). Although the DTM can be edited to add break lines and delete extraneous surfaces resulting from vegetation, no such editing was performed since the DTM was being used primarily for discontinuity measurements.

Define Features and Perform Analyses

The feature-picking tool of the software was used to measure 238 rock discontinuities (bedding planes and joints) within the 420-foot-long section of roadway encompassed by the digital model (Figure 7b). Locations and types of measurements are indicated by colored disks. Bedding planes are represented by green disks, joints by yellow disks, and the contact between the Tuscarora and Juniata Formations by a red disk (Figure 8). The disks are drawn in proportion to the extent of the points digitized while delineating the feature, so disk size denotes the relative magnitude of the feature. In addition to orientation, the feature-picking tool provides location coordinates of the feature and the magnitude of the feature (Figure 9).

Although the tops of bedding planes were generally not observable in the model due to the upward tilt of the camera during image acquisition, the model permitted delineation of bedding planes based on the change in the location of their traces across the surface of the digital terrain model. Since the camera bearing was generally to the southwest when the photos were taken, joint faces striking north and northwest are more readily apparent in the photographs. The

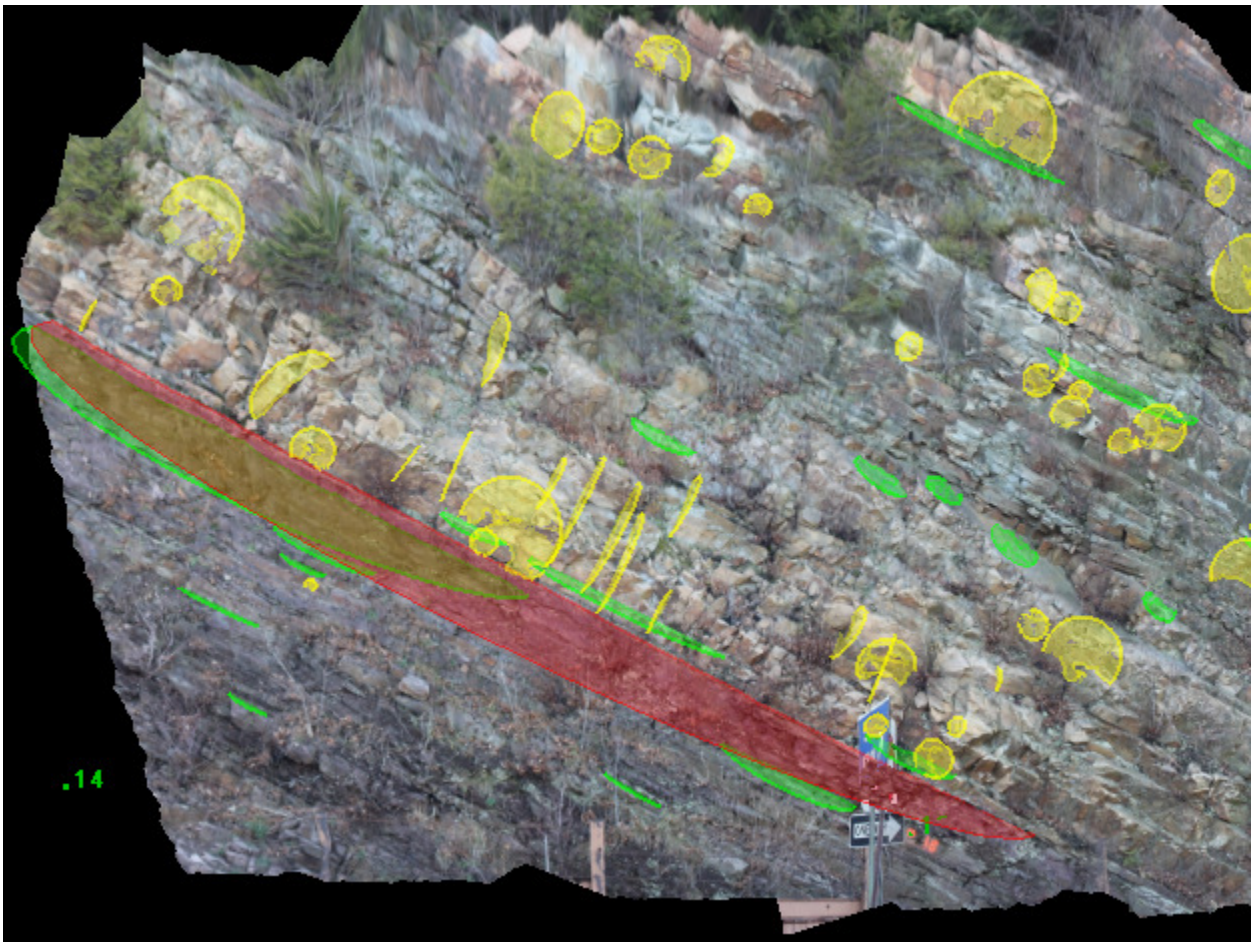

FIGURE 8 Portion of digital model showing measured bedding joints (green disks); non-bedding joints (yellow disks), and the Tuscarora/Juniata contact (red disk). Red disk is 74.3 feet (22.6 meters) diameter.

tops of some more steeply dipping beds are evident is some locations in the model. These beds appear to be foreset beds.

FIELD RECONNAISSANCE

Reconnaissance of the existing rock slope was performed following development of the model in order to collect additional data and validate the model. An additional 36 rock discontinuities were measured using a Brunton Geotransit with the magnetic declination set to 11.5 degrees west. Measurements were collected from areas north and south of the limits of the digital photogrammetry model and the area behind the existing wall. Some large, conspicuous faces within the model area were also measured for model validation. Figure 10 provides a stereonet plot of the dip vectors of the discontinuity orientations measured using the digital photo model and measured using the Brunton Geotransit. The digital photogrammetry measurements compare favorably with the manual measurements.

Additional reconnaissance was performed to examine the outcrop for clay seams encountered in test borings performed as part of the subsurface investigation. Projecting the clay seams to the surface of the digital image was useful in identifying the possible location of the clay seams in the outcrop face (Figure 11). Reconnaissance also permitted collection of

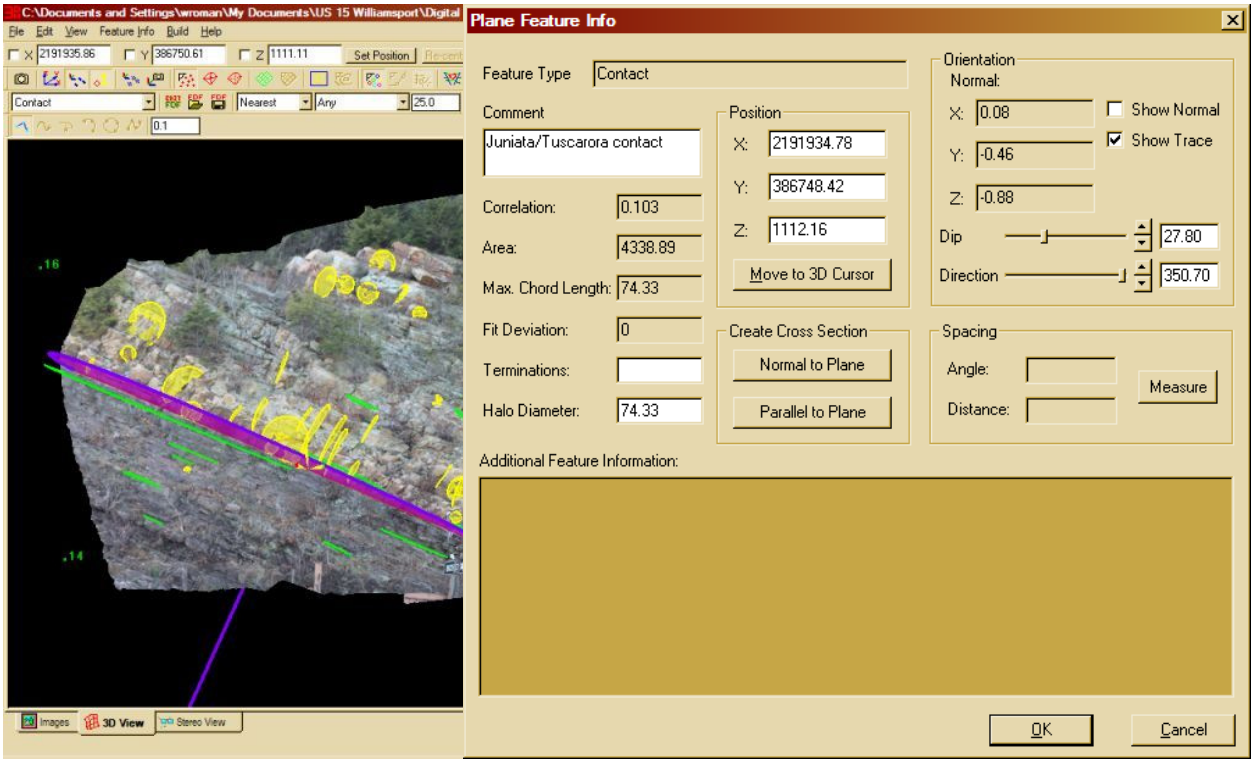

FIGURE 9 Dialog box with selected feature information.

information not available from the digital imaging, such as measurement of fallen block sizes and observation of seepage conditions, joint roughness, weathering, slickensided surfaces, and joint in-fillings.

ROCK FACE CHARACTERIZATION

Discontinuities of two types were identified—bedding joints (including the contact between the Tuscarora and Juniata Formations) and two sets of steeply dipping joints. The great circles and dip vectors corresponding to the 273 measurements taken on the three joint sets are plotted on stereonets in Figure 12. Joint set 1 consists of bedding joints dipping to the north. Joint set 2 consists of joints striking north-south and dipping steeply to the east and west, and joint set 3 consists of joints striking east-west and dipping steeply to the south. Histogram analyses of bedding dip angle and dip direction and jointing dip angle are also provided in Figure 12.

STEREONET ANALYSES

The discontinuity orientation data were analyzed using stereonets to assess the kinematic possibility of planar and toppling failures along the measured discontinuities and the kinematic possibility of wedge failures along the lines of intersection between the measured discontinuities. A friction angle of 27 degrees was used in the analyses given the presence of seeps, as indicated by water and ice noted on some bedding planes during the site reconnaissance, and the presence of numerous shale and siltstone beds, which tend to deteriorate over time and undercut the quartzite beds in the Tuscarora Formation, and to a lesser extent, the sandstone beds of the Juniata Formation. During the site reconnaissance, slight displacement of rock blocks was noted on bedding surfaces having dips as shallow as 29 degrees.

The potential for planar and toppling failure was assessed by using stereonets to plot discontinuity dip vectors and to identify the critical area associated with varying cut slopes and slope directions along the curved highway alignment. To assess wedge failures, a matrix of vector cross product equations was solved to determine the lines of intersections between bedding and jointing and between the east-west and north-south striking joints. A contour plot of the lines of intersections was used to assess the kinematic potential for wedge failure for alternate cut slope designs (Figure 13).

The stereonet analyses were generally favorable with respect to the principal components of bedding and jointing; however the analyses indicated planar and wedge failures are kinematically possible at the fringes of the discontinuity sets toward the northern end of the study area, and toppling is a possibility, particularly in the steeper portions of the northern half of the study area.

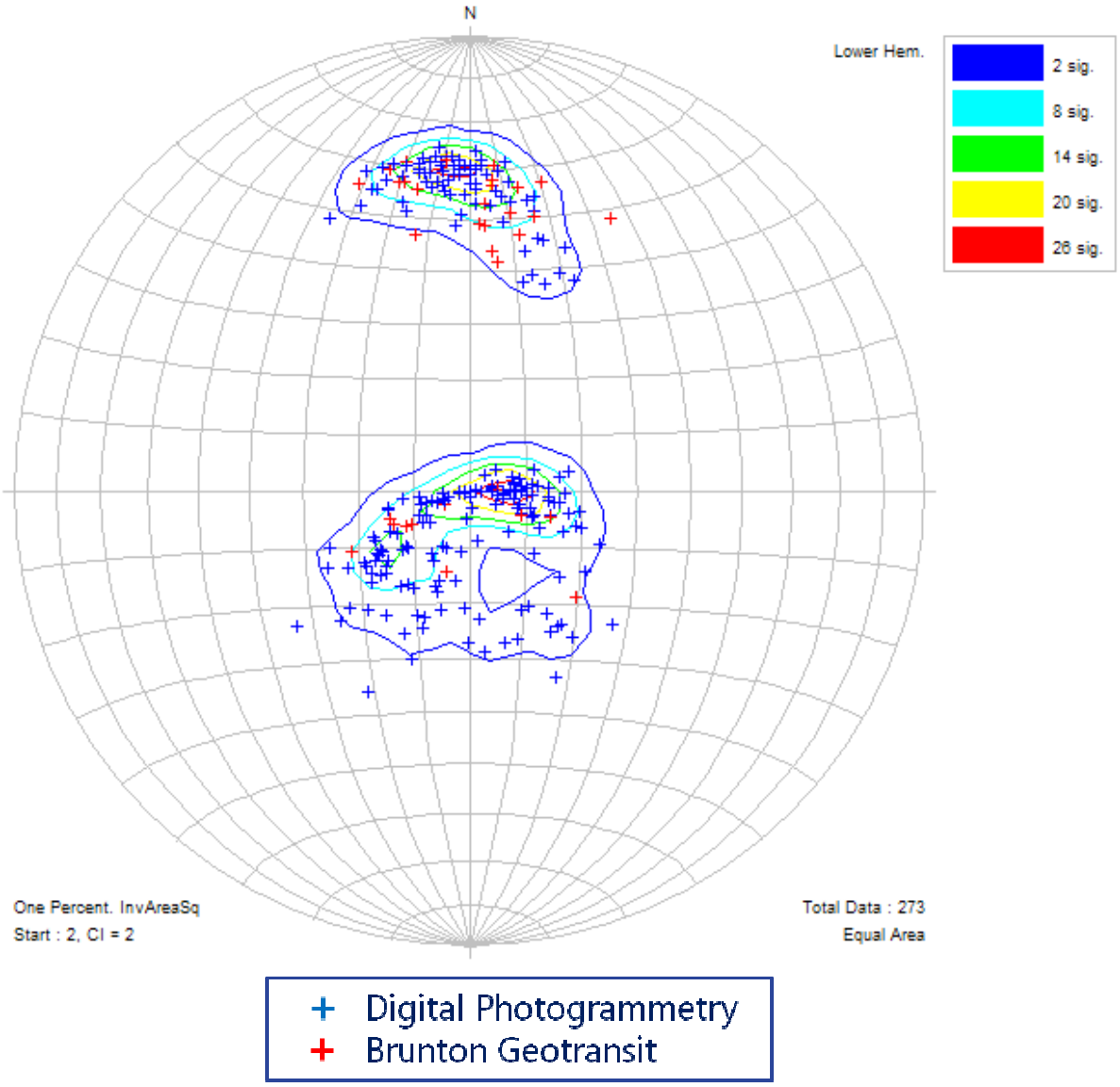

FIGURE 10 Comparison of digital photogrammetry and manual measurements.

FIGURE 11 Weathered shale bed possibly correlating with clay seam encountered in test boring.

SUBSURFACE INVESTIGATION

Six core borings were drilled. Overall core recovery was 96.3 percent. Core recovery was slightly higher in the Juniata Formation (98.2 percent) than in the Tuscarora Formation (95.5 percent). Overall Rock Quality Designation (RQD) was 65.8 percent, which indicates generally fair quality rock. RQD was slightly higher in the Juniata Formation (68.1 percent) than in the Tuscarora Formation (64.8 percent). Boring logs indicate bedding dips ranging from 22 to 28 degrees in the Juniata Formation and generally from 16 to 32 degrees in the Tuscarora Formation; however, dips as steep as 40 degrees were sometimes noted in the latter formation. These observations are generally consistent with observations from the digital photogrammetry model and manual measurements. Spacing and orientation of non-bedding joints noted in the boring logs are also generally consistent with observations from the 3D model and from site reconnaissance.

OTHER ANALYSES

In addition to the discontinuity analyses, other analyses factored into the rock cut slope design included laboratory analyses of clay samples from test borings (residual shear and fully softened direct shear tests), stability calculations using the factor of safety formula of Hoek and Bray *(8)*, and rockfall catchment zone analyses using the Colorado Rockfall Simulation Program *(9)*, and the Ritchie ditch design chart *(10)*. The stability calculations considered the potential sliding (plane) failure occurring along clay seams and factored in water pressure building up along the clay seams and within a tension fracture forming the upper release surface for the sliding rock

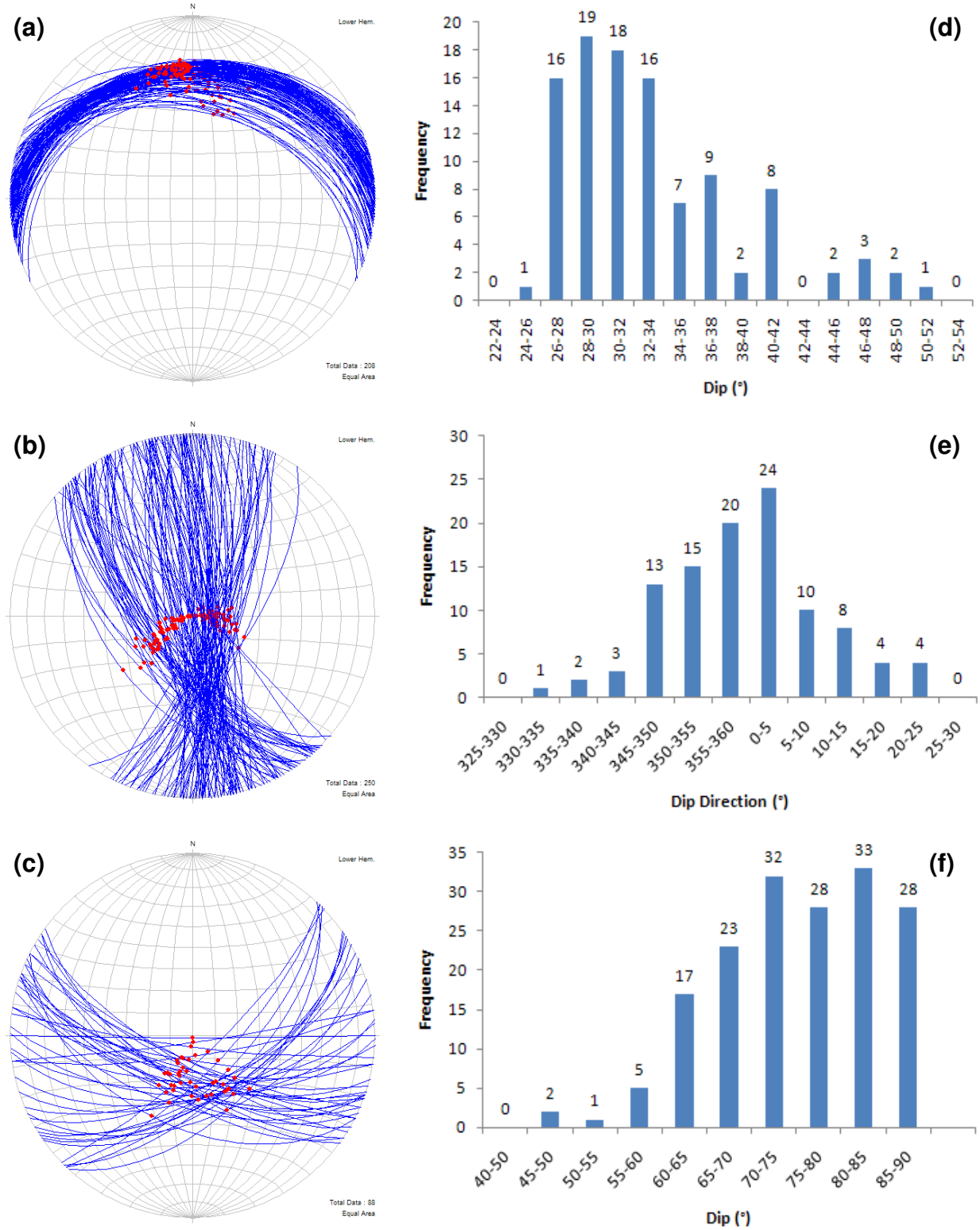

FIGURE 12 Great circles (blue lines) and dip vectors (red dots) of (a) joint set 1 (bedding), (b) joint set 2, and (c) joint set 3. Histogram analyses of (d) bedding dip angle, (e) bedding dip direction, and (f) jointing dip angle.

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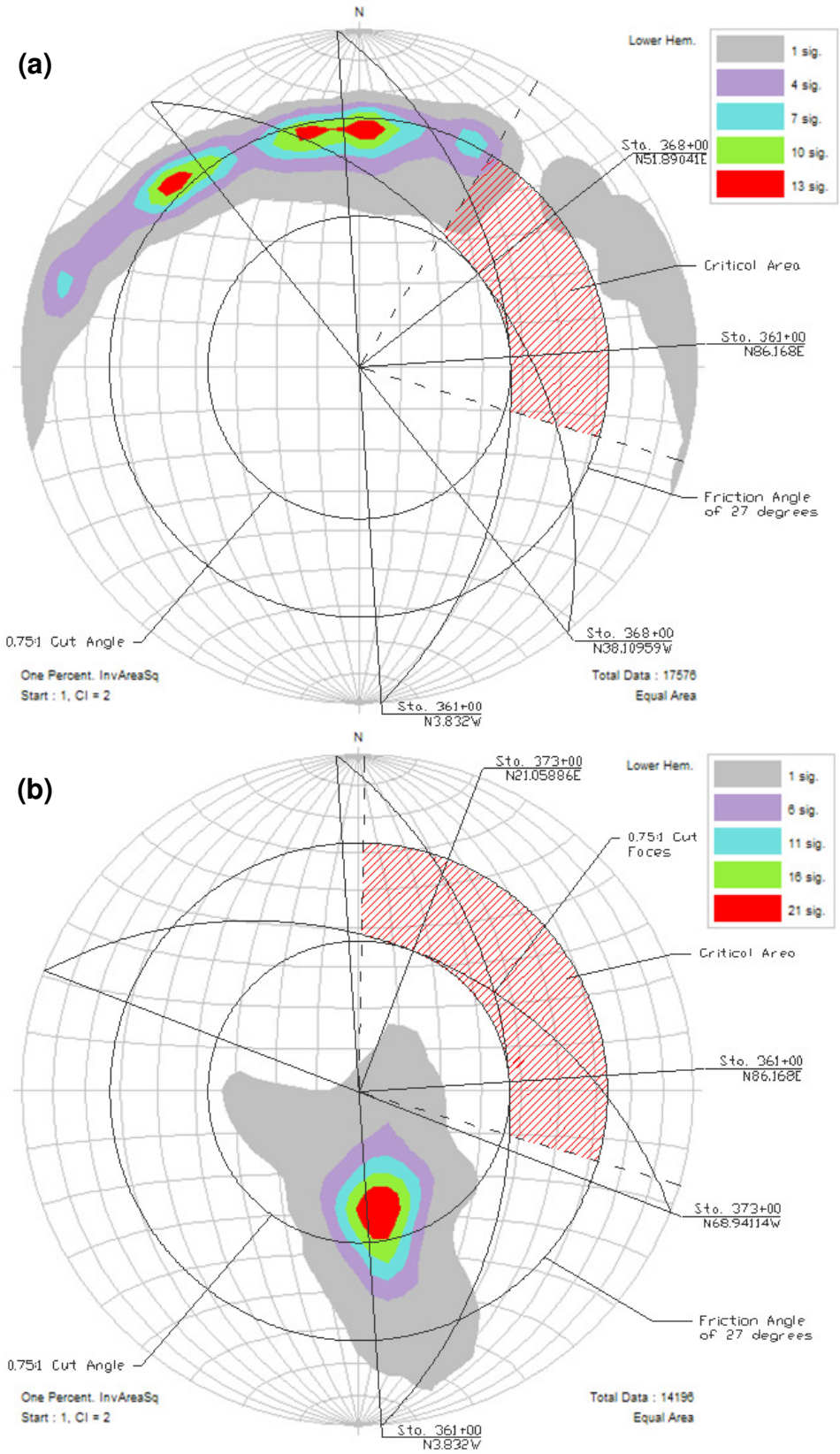

FIGURE 13 Kinematic analyses for wedge failures using contour density plots of lines of intersections between (a) bedding and jointing, and (b) joint sets 2 and 3.

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mass. The stability calculations used a cohesion value of 300 pounds/foot^2 (0.29 kPa) and a friction angle of 20 degrees.

ROCK CUT SLOPE DESIGN

Rock cut slopes ranging from 1.5H:1V to 1H:1V were recommended along various portions of the alignment. In transition zones between the recommended rock cut slopes, it was recommended that smooth, linear transitions be provided and that adverse rock slopes dipping between N30°W and N30°E be avoided. Although stereonet analyses indicated steeper cut slopes were possible in portions of the cut, these areas were not of sufficient extent to warrant steepening the proposed cut slope, especially since steepening the cut slope tended to create transition zones having adverse orientations.

A rock catchment basin was recommended because of the remaining rockfall potential and instabilities that may develop over time as a result of natural rock weathering processes, including free-thaw cycles, undercutting due to differential weathering of the shale and siltstone beds, and leveraging by vegetation. Horizontal drain holes were recommended to improve the factor of safety with respect to sliding along clay seams encountered in test borings. The drain hole orientation was optimized using the vector dot product formula and average joint orientations and typical spacing. The rock cut portion of the project is expected to be completed in 2012.

APPLICATION OF DIGITAL PHOTOGRAMMETRY

Digital photogrammetry worked quite well on this project. The discontinuity measurements from the digital photogrammetry model were used in the stereonet analyses of the kinematic potential for plane, wedge, and toppling failures. The measurements were also used in optimizing the azimuth of horizontal drains proposed to reduce water pressure within the rock mass and improve cut slope stability. Having the coordinates of each measurement permitted analysis of the variability of bedding dip angle and dip direction along the curving highway alignment. The digital model was also useful for locating the possible outcrops of clay seams encountered in test borings.

This project illustrated some of the advantages of using digital photogrammetry for rock cut slope design. Specific advantages include the following:

1. Data can be collected safely from challenging to reach areas with no rappelling or free climbing.
2. Exposure to traffic, rockfalls, and inclement weather is significantly reduced.
3. A robust set of measurements can be collected in a short period of time.
4. There is no need to set up and measure traverses since the software provides coordinates of each measurement.
5. Discontinuities are measured across a greater area of their extent than can be measured by hand.
6. Discontinuities with limited exposure are easily measured by digitizing their trace across the outcrop model.
7. Measurements are fitted to the digital image of the rock face, which can be rotated and viewed edge-on to assess the closeness of the fit.
8. Having the coordinates of each discontinuity measurement facilitates analysis of the variability of bedding dip and dip direction along the roadway alignment.

9. Human error in recording the measurements is reduced since the measurements are recorded by the computer.
10. Shallow dipping (<5 degrees) joints, which can be very challenging to measure with a compass, can be easily measured by digitizing their trace along the digital model.

Although useful for quickly and safely collecting discontinuity orientation data required for kinematic analyses, digital photogrammetry may not permit measurement of fallen block sizes and observation of seepage conditions, joint roughness, weathering, slickensided surfaces, and joint in-fillings needed for other analyses factored into the design of a rock cut.

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