Rockfall Hazard Rating System: Benefits of Utilizing Remote Sensing

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Key Terms: Remote Sensing, Rockfall, Hazard, Landslide, Engineering Geology

ABSTRACT

Transportation corridor slopes have the potential to be hazardous to adjacent assets. The Rockfall Hazard Rating System (RHRS) is a stepwise process designed to identify potentially hazardous slopes by assigning a hazard rating that determines the order by which to mitigate and remediate slopes. The traditional RHRS approach is field-based: observations are made by a field crew who convert observations into slope ratings (preliminary and detailed). The purpose of this study is to examine the benefits of utilizing remote sensing techniques on 14 slopes within a 24-km railroad corridor in southeastern Nevada. Remote sensing allows for data acquisition in difficult-to-reach locations from various view angles. Images and data from three remote sensing technique-platform combinations are examined: optical imagery acquired via satellite, unmanned aerial vehicle, and LiDAR data acquired from a stationary sensor. Detailed RHRS slope ratings from both sets of optical images are compared to two types of field-based ratings: (1) initial field observations performed using the traditional RHRS approach and (2) average detailed rating scores from six participants (geologists and geotechnical engineers) given field notes of the 10 rating criteria for the 14 slopes. Terrestrial LiDAR is capable of monitoring slow slope deformation, with an accuracy of approximately 2 cm/yr, and identifying areas of rapid deformation. Remote sensing techniques should not entirely replace traditional field methods. Instead, developing an approach that combines the advantages of field- and remote sensing–based methodologies will enable transportation agencies to ensure a more robust, efficient, and time-effective RHRS approach.

INTRODUCTION

The Rockfall Hazard Rating System (RHRS) is a procedure used to analyze and prioritize slopes along transportation corridors (roadways and railways) based on the potential hazard of rockfall occurrence. A train derailment in British Columbia, Canada, in the early 1970s was the impetus for the development of the RHRS, which is commonly used today (Brawner and Wyllie, 1975). Rating criteria based on geometric and geologic conditions of the railroad-slope environment were created to determine future rockfall mitigation and remediation efforts. Slopes were categorized by greatest potential hazard (A) to least hazardous (E). This novel approach was expanded (Wyllie et al., 1979; Wyllie, 1980, 1987) with the development of an exponential scoring system to better categorize slopes from A to E. The practicality of this proactive approach was adopted by many transportation agencies in the early 1990s when state agencies collaborated to develop the initial RHRS instructions (Pierson, 1991, 1992; Pierson and Van Vickle, 1993; and Brawner, 1994). Since then some transportation agencies have further refined the slope hazard rating criteria (Huang et al., 2009). The RHRS procedure described by Pierson and Van Vickle (1993) will be used in this article, since this version is incorporated into most recent RHRS versions.

The full RHRS procedure requires completion of the following six steps: (1) slope inventory, (2) preliminary slope rating, (3) detailed slope rating, (4) project design and cost estimation, (5) project identification and development, and (6) yearly reviews and updates. The data collected in these six steps are then input into a geodatabase that also incorporates the locations of slopes adjacent to relevant transportation corridors (Step 1).

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The preliminary slope rating (Step 2) classifies slopes into three hazard categories—A (high), B (moderate), and C (low)—based on past rockfall activity and the potential for future rockfall activity. The detailed slope rating (Step 3) further classifies high-risk slopes (from the preliminary slope rating) by assigning a score based on 10 rating criteria that include (1) slope height, (2) ditch effectiveness, (3) average vehicle risk, (4) decision sight distance, (5) roadway width, (6) structural condition, (7) rock friction (hard rock) or differential erosion rates (soft rock), (8) block size/volume, (9) climate and water presence, and (10) rockfall history. Scores range from 1 (lowest hazard) to 100 (highest hazard), per rating criteria. The detailed rating for each slope is the summation of all 10 rating criteria scores. Project design and cost estimation (Step 4) is considered prior to project implementation. Pierson and Van Vickle (1993) offer a variety of methods for project identification and development based on the RHRS procedure. The purpose of Step 5 is to formulate the best approach for rockfall mitigation and remediation construction, while Step 6 recommends rated slopes to be reviewed on an annual basis. Therefore, depending on the outcome of Step 6, changes to information recorded in Steps 1 through 5 may be required for relevant slopes.

Implementation of the complete RHRS procedure can be time-consuming and expensive as a result of the amount of data acquisition and analysis (preliminary and detailed slope ratings) required, which increases drastically with scale (e.g., state-wide transportation networks), and the need for annual reviews and updates. Transportation agencies have investigated using different types of non-traditional data acquisition techniques to minimize these difficulties. Traditional data acquisitions are in situ measurements and/or field observations, in which the instrument and the user need to be on site. Non-traditional data acquisitions are remote sensing–based, in which active or passive sensors mounted upon moving or stationary instruments receive information in the form of electromagnetic waves (e.g., aerial photography). The use of remote sensing data acquisition for RHRS purposes—such as slope characterization, feature identification, and surficial change and displacement measurements—has evolved over the last 15 years. Data sources include state highway video logs (Maerz et al., 2005; Youssef et al., 2007; and Youssef and Maerz, 2012), optical photography and photogrammetry (Di Crescenzo and Santo, 2007; Lucieer et al., 2013), terrestrial laser scanning (Bauer et al., 2005; Abellán et al., 2009, 2010), and light detection and ranging (LiDAR) technologies (Strouth and Eberhardt, 2007; Lato et al., 2009, 2012; and Lan et al., 2010). Terrestrial remote sensing techniques allow for detailed observations and accurate surficial measurements of slopes. Platforms in motion, such as satellites, airplanes, terrestrial vehicles, and unmanned aerial vehicles (UAVs), allow for data acquisitions that cover relatively large areas (potentially multiple slopes at once) at various vantage points in a repeatable fashion.

A 24-km section of railroad corridor in southeastern Nevada (Figure 1) was chosen to test the efficacy of applying two remote sensing methods—optical photogrammetry and LiDAR, with instruments located on different platforms and viewing angles (Table 1)—to develop an RHRS rating for slopes within the corridor. The railroad corridor follows the valley floor of a canyon system through volcanic rock consisting of rhyolite, tuff, and welded breccia, with approximately 33 percent of railroad tracks within 30 m of a slope with a height greater than 50 m. Approximately 2.5 percent of the 24-km track passes through five tunnels.

The railroad corridor was studied by Justice (2015), who utilized a multi-level approach through the application of the RHRS procedure. The multi-level approach, which examined local- and regional-scale hazard assessments, was performed using satellite orthophotography and point-cloud images generated from a terrestrial LiDAR survey on three slopes within the railroad corridor. Bouali et al. (2016) used a satellite-based remote sensing technique, Interferometric Synthetic Aperture Radar (InSAR), to measure surficial displacement rates across the railroad corridor between 1992 and 2010; this study included all three slopes from the Justice (2015) study. One slope exhibited downslope displacement rates greater than 10 mm/yr, and five additional slopes were identified as potentially hazardous, based on slope distance from railroad track, slope height, slope angle, downslope displacement rate (velocity), and total displacement.

This study will focus on 14 slopes (named Slope 1, Slope 2, . . . , Slope 14) that meet three geometric criteria: (1) the slope toe is located within 15 m of the railroad track, (2) the slope is at least 15 m in height, and (3) a dip greater than 25° toward the railroad tracks is measured on the slope face. The purpose of this study is to investigate the effectiveness of using remote sensing techniques to assess RHRS values compared to the traditional field-based method. Although some state transportation agencies continuously monitor and rate their highest priority slopes (e.g., through video logs), a synergistic field- and remote sensing–based approach will allow for measurements that are undetectable or not within view from transportation corridor heights, such as identification of rockfall source areas and unstable blocks, small-scale rock displacement detection (millimeter-scale), and identification of potential future hazardous slopes.
Figure 1. Twenty-four–kilometer segment of railroad corridor located in southeastern Nevada (inset). The 14 slopes (green circles) are identified by number (Slope 1, Slope 2, etc.). Background imagery was generated in ArcGIS software by Esri.
Table 1. Types of remote sensing platforms, sensors, and output data used in this study.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensors</th>
<th>Sensor Type</th>
<th>Motion</th>
<th>Output Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>Landsat 7, WorldView 1 &amp; 2</td>
<td>Optical</td>
<td>Polar Orbit</td>
<td>Photographic Images</td>
</tr>
<tr>
<td>UAV</td>
<td>Nikon D800 (50 mm) mounted on Bergen Hexacopter</td>
<td>Optical</td>
<td>Remote Controlled by Operator</td>
<td>Photographic Images, 3-D Point Clouds</td>
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<tr>
<td>Terrestrial</td>
<td>RIEGL LMS-Z210ii</td>
<td>LiDAR</td>
<td>Stationary</td>
<td>3-D Point Clouds</td>
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</table>

Specifically, additional advancements in the use of remote sensing techniques for preliminary slope ratings, detailed slope ratings, and annual rating reviews and updates would supplement repetitive site visits yet complement the traditional RHRS field-based approach. A long-term monitoring approach that updates slope ratings in near real-time would be beneficial and could be accomplished by incorporating remote sensing techniques into RHRS procedures.

**METHODOLOGY**

The application of remote sensing techniques in acquiring information for Step 2 (preliminary slope rating), Step 3 (detailed slope rating), and Step 6 (yearly reviews and updates) can aid in the efficacy of the RHRS procedure discussed in Pierson and Van Vickle (1993). Preliminary slope ratings can be assigned to slopes based on the “estimated potential for rockfall on roadway” and the “historical rockfall activity” using a three-tiered class system: “A” for high, “B” for moderate, and “C” for low (p. 18, Pierson and Van Vickle, 1993). A total of eight factors are considered when performing the preliminary rating. Of these eight factors, four potential rockfall factors can also be estimated using remote sensing data if these data were acquired after the rockfall event and prior to remediation. This study will examine the four potential rockfall factors; a similar approach can be applied to the historical rockfall activity factors if relevant data were acquired.

Optical photography, acquired by satellite, airplane, or UAV fly-overs, can directly aid in the quantification of factors that indicate the potential for future rockfall events that impact the adjacent transportation corridor. All four factors are area measurements (rock size, material quantity, material amount, and ditch coverage) and, therefore, can be estimated using optical photographs in a geographic information system (GIS) database. Two acquisition variables that dictate the effectiveness of optical photograph usage are image resolution and view angle. Coarse-resolution (meter-scale) images are widely available and are sufficient for identifying large unstable blocks, but there are likely to be sub-meter-scale rocks that can cause damage and will be undetectable at such coarse resolution. It is therefore important to obtain optical photographs at a resolution greater than (lower in magnitude) the smallest-sized rock deemed dangerous to traffic within the transportation corridor, most likely images with centimeter-scale resolution. The view angle from which the images are acquired is also important, as different vantage points give more information on the slope. For situations in which the top of the slope is not viewable at the transportation corridor (ground) level, a vertical view angle allows for better estimations of the material quantity and amount of material available, as well as for identification of potential large unstable blocks that were previously unobservable.

**Preliminary Slope Rating (RHRS Step 2)**

The preliminary slope rating classifies a slope based on the “estimated potential for rockfall on roadway” and the “historical rockfall activity” using a three-tiered class system: “A” for high, “B” for moderate, and “C” for low (p. 18, Pierson and Van Vickle, 1993). The overall rating factors are considered when performing the preliminary rating. Of these eight factors, four potential rockfall factors can be estimated using remote sensing. These factors are (1) size of rockfall material, (2) quantity of material, (3) amount available, and (4) ditch effectiveness. The four historical rockfall activity factors can also be estimated using remote sensing data if these data were acquired after the rockfall event and prior to remediation. This study will examine the four potential rockfall factors; a similar approach can be applied to the historical rockfall activity factors if relevant data were acquired.

Optical photography, acquired by satellite, airplane, or UAV fly-overs, can directly aid in the quantification of factors that indicate the potential for future rockfall events that impact the adjacent transportation corridor. All four factors are area measurements (rock size, material quantity, material amount, and ditch coverage) and, therefore, can be estimated using optical photographs in a geographic information system (GIS) database. Two acquisition variables that dictate the effectiveness of optical photograph usage are image resolution and view angle. Coarse-resolution (meter-scale) images are widely available and are sufficient for identifying large unstable blocks, but there are likely to be sub-meter-scale rocks that can cause damage and will be undetectable at such coarse resolution. It is therefore important to obtain optical photographs at a resolution greater than (lower in magnitude) the smallest-sized rock deemed dangerous to traffic within the transportation corridor, most likely images with centimeter-scale resolution. The view angle from which the images are acquired is also important, as different vantage points give more information on the slope. For situations in which the top of the slope is not viewable at the transportation corridor (ground) level, a vertical view angle allows for better estimations of the material quantity and amount of material available, as well as for identification of potential large unstable blocks that were previously unobservable.

**Detailed Slope Rating (RHRS Step 3)**

Slopes with a preliminary “A” rating are of highest priority, requiring that detailed slope ratings be conducted on these slopes first (Pierson and Van Vickle, 1993). The detailed slope rating assigns a numerical value between 1 (lowest hazard) and 100 (highest hazard) for the 10 rating criteria previously discussed. Five of the rating criteria are quantitative, with the function...
In terms of hazards posed by unstable slopes, one way to "A"-rated slope (RHRS Step 3). This provides a long-term monitoring procedure that is focused on the most hazardous slopes. Furthermore, any preliminarily rated slope (regardless of tiered rating: A, B, or C) that has undergone any changes (construction, maintenance, displacement, etc.) should be re-reviewed and the slope rating updated.

A major benefit of utilizing remote sensing techniques in assessing the RHRS parameters is the capability of monitoring slope changes over long periods of time. Multiple acquisitions of LiDAR and optical photogrammetry can qualitatively monitor changes as well as quantitatively measure deformation rates on and around each slope. Annual-scale qualitative observations may include noting (1) the change of talus sizes at the bottom of the slope, (2) the weathering condition and erosion locations on the slope face, and (3) the presence of water in planes of weakness (faults, joints, bedding planes), among others. Quantitatively, LiDAR and optical photogrammetric techniques such as Structure from Motion (SfM) and three-dimensional point-cloud change detection allow for the calculation of superficial deformation between image pairs by calculating the change in the location of the slope surface, at two different acquisition dates, and in three-dimensional space.

RESULTS AND DISCUSSION

Examples of remote sensing data analyses applied to the RHRS procedure are organized by RHRS step. The effectiveness of optical satellite and UAV photogrammetry are examined in “RHRS Step 2: Preliminary Slope Rating.” Those two techniques are compared to two field-based approaches—an initial field examination and a participant survey—in “RHRS Step 3: Detailed Slope Rating.” Long-term remote sensing–based slope monitoring approach are discussed in “RHRS Step 6: Yearly Review and Update,” with a LiDAR change detection example given of Slope 1.

Preliminary Slope Rating (RHRS Step 2)

Preliminary slope ratings were assigned to all 14 slopes via both traditional field-based observations and using optical satellite images (Table 2). The field approach identified three “A”-rated slopes, nine “B”-rated slopes, and two “C”-rated slopes. The satellite imagery approach identified one “A”-rated slope, seven “B”-rated slopes, and six “C”-rated slopes. An under-estimation of preliminary slope ratings using optical satellite imagery is likely due to the use of coarse-resolution imagery (meter-scale). Sub-meter-scale details are unobservable and blurry at coarse resolutions,
Table 2. Preliminary slope ratings for each slope using field-based observations and optical satellite imagery.

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<tr>
<th>Slope #</th>
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resulting in hazardous features (e.g., moderate-sized loose rocks, adverse joint orientations, and other evidence of displacement) that go undetected. This underestimation issue is addressed more fully in “RHRS Step 3: Detailed Slope Rating.” Although small-scale details may be unobservable with coarse-resolution imagery, other steps within the RHRS procedure can be made easier when this imagery is supplemented with optical satellite imagery. Coarse satellite imagery can be obtained free of charge and in near real-time, which can aid in large-scale rockfall detection and monitoring.

Vertical optical imagery can greatly assist in the preliminary slope rating RHRS step. Figure 2 shows Slope 1—the only slope in which historic rockfalls have blocked and disrupted rail traffic—from three vantage points: (A) at ground level near the railroad tracks, (B) through near-vertical optical image acquired via satellite, and (C) through vertical optical image acquired via UAV. Many slope features were identified with satellite and UAV imagery that were undetected from ground level. Features identified using satellite imagery include at least three large blocks at the top of the slope and the presence of the main scarp (Figure 2B [red dashed oval] and C), although accurate measurements as to the size of the main scarp were difficult to obtain. The aperture of the main scarp was estimated using UAV images (and confirmed by field work) to be about 8 m wide. Additional features detected with UAV imagery include the presence of a secondary scarp, located downslope from the main scarp, as well as large blocks and piles of loose rock (also downslope from the main scarp).

Detailed Slope Rating (RHRS Step 3)

A detailed slope rating is normally performed on slopes that received an “A” rating in the preliminary slope rating step. This is usually due to the sheer quantity of slopes that may be classified as “A” level, especially when dealing with state-wide transportation networks (Pierson and Van Vickle, 1993). However, since the areal extent of this project is relatively small, all

Figure 2. Slope 1. (A) Photo taken from ground level near the railroad tracks. (B) Near-vertical optical satellite image. Peak 1 from (A) is shown in white circle. Slope features that aid in the preliminary slope rating include at least three large blocks and the main scarp (red dashed oval). (C) Vertical UAV image that details the main scarp (up to 8 m wide) and a previously undetected secondary scarp, a large block also identified in (B), and piles of loose rock.
Remote Sensing for RHRS

Table 3. Preliminary slope ratings based on field observations and satellite imagery (also shown in Table 2). Detailed slope ratings based on initial field observations. Rating criteria listed by number: 1 = slope height, 2 = ditch effectiveness, 3 = average vehicle risk, 4 = decision sight distance, 5 = roadway width, 6 = structural condition, 7 = rock friction, 8 = block size/volume, 9 = climate and presence of water, and 10 = rockfall history. Rating criteria in boldface were calculated using exponent formulae from Pierson and Van Vickle (1993).

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<th>Slope No.</th>
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</table>

Table 4 displays information for all field-based detailed rating scores. The “initial score” is the detailed rating score obtained by the original field crew. The minimum and maximum “participant scores” illustrate the range in detailed rating scores assigned based on the same set of textual and numerical field notes. The initial score and participant scores were generally in agreement: the initial score fell into the participant score range for nine slopes (Slopes 2, 4, 5, 7, 8, 9, 11, 12, and 14); the initial score was greater than the participant score range for Slopes 1 and 3; the initial score was less than the participant score range for Slopes 6, 10, and 13. The participant scores ranges were within 72 for every slope except Slope 14. Discrepancies in detailed rating scores were usually due to the interpretation of subjective textual rating criteria, especially when complex slope characteristics did not neatly compartmentalize into a pre-assigned rating criteria score. For example, the structural condition of a rock slope is assigned a rating criteria score of 3 if there are “discontinuous joints, favorable orientation,” a score of 9 for “discontinuous joints, random orientation,” a score of 27 for “discontinuous joints, adverse orientation,” and a score of 81 for “continuous joints, adverse orientation” (p. 26, Pierson and Van Vickle, 1993). Subjectivity occurred when slopes were described as having “continuous joints, random orientation,” which is not a predetermined category, and, therefore, the value of structural condition rating criteria is left for the participant to decide. This type of subjective score assignment was required for multiple slopes because selecting a quantitative value for these rating criteria was sometimes difficult as a result of complex geology.

Table 4. Detailed slope ratings. “Initial score” is identical to initial field-based observations found in Table 3. Statistics of “participant scores” (mean, standard deviation, minimum, and maximum) from the survey illustrate the subjectivity of the RHRS procedure.

<table>
<thead>
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<td>409</td>
<td>447</td>
</tr>
</tbody>
</table>
Detailed slope ratings were also assigned using optical photography obtained from two platforms: satellite and UAV. The remote sensing–based RHRS detailed slope rating approach was conducted by downloading the data (in the case of satellite images) or acquiring data (UAV images) and then identifying rating criteria from the images obtained of each slope within the study site. Measurements were made after importing the images into a GIS for analysis.

Optical satellite photography data were obtained from a combination of Landsat 7, WorldView 1, and WorldView 2 acquisitions; detailed rating scores are listed in Table 5. Satellite-based detailed rating scores were generally lower than field-based detailed rating scores, as 11 of 14 slopes followed this trend. This score underestimation was likely due to the relatively coarse resolution (meter-scale) of the WorldView satellite imagery. Sub-meter-sized features such as joints, faults, bedding planes, zones of erosion and weathering, and the presence of water were unobservable with coarse-resolution images. Adding to the difficulty was the fact that satellite images were acquired at near vertical, and shadows were present across the slope face (Figure 3A), resulting in a loss of information.

<table>
<thead>
<tr>
<th>Slope No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
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</thead>
<tbody>
<tr>
<td>Initial field-based scores</td>
<td>506</td>
<td>334</td>
<td>332</td>
<td>269</td>
<td>250</td>
<td>327</td>
<td>467</td>
<td>329</td>
<td>325</td>
<td>350</td>
<td>359</td>
<td>427</td>
<td>328</td>
<td>308</td>
</tr>
<tr>
<td>Mean field-based participant scores</td>
<td>452</td>
<td>357</td>
<td>313</td>
<td>283</td>
<td>259</td>
<td>402</td>
<td>492</td>
<td>344</td>
<td>325</td>
<td>419</td>
<td>359</td>
<td>433</td>
<td>393</td>
<td>362</td>
</tr>
<tr>
<td>Optical satellite</td>
<td>487</td>
<td>331</td>
<td>304</td>
<td>244</td>
<td>208</td>
<td>369</td>
<td>352</td>
<td>293</td>
<td>350</td>
<td>265</td>
<td>294</td>
<td>357</td>
<td>318</td>
<td>282</td>
</tr>
<tr>
<td>Optical UAV</td>
<td>528</td>
<td>396</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

n/a - not applicable; data not obtained by method for specified slopes.

Figure 3. Images of Slope 2 taken from three view angles: (A) optical satellite image, (B) vertical optical UAV image, and (C) oblique optical UAV image. A yellow triangle is placed in each image for geographic reference.
Although the use of optical satellite imagery was relatively beneficial for the preliminary slope rating, the coarse resolution and view angle make relying on satellite imagery for the detailed slope rating difficult. Consistent underestimation of detailed rating scores, when compared to the field-based approach, may result in the miscalculation of potential hazard levels. It would be unacceptable if a catastrophic event (e.g., large rockfall) that went unpredicted and unmitigated occurred as a result of coarse resolution imagery. Therefore, the exclusive use of coarse-resolution satellite imagery for the detailed slope rating RHRS step is insufficient and dangerous, making it necessary to use higher resolution imagery.

Optical UAV photographs were acquired using a Nikon D800 camera, with a 50-mm prime lens (collecting 36-megapixel imagery at 2 frames/s at a speed of approximately 2 m/s) onboard a Bergen Hexacopter for Slopes 1 and 2. Detailed rating scores are shown in Table 5. High-resolution imagery (centimeter-scale), obtained from multiple UAV fly-overs at different view angles (vertical and oblique), results in an overestimation of detailed rating scores when compared to both field-based methods and optical satellite photography usage. For example, vertical (Figure 3B) and oblique (Figure 3C) view angles of Slope 2 present a more complete picture of current slope conditions. A vertical view angle allows for the identification of source material for potential instabilities on the top of the slope, vegetation distribution (a vegetated region has not experienced a rockfall recently), and structural conditions, such as weathering distribution and strike of joints/faults. An oblique view angle reveals more of the upper slope face, which is difficult to see from ground level. An overestimation of detailed rating scores was the result of more robust data. Table 6 shows the increase in UAV-based detailed rating scores compared to satellite-based detailed ratings scores. Regarding Slope 2 (Figure 3), an increase in three rating criteria changed the detailed rating score from 331 (satellite) to 396 (UAV). An increase in the three rating criteria values—structural condition, rock friction, and block size/volume—was a direct result of better estimations due to higher resolution imagery. The use of sub-meter UAV imagery makes unstable rocks, ranging in size from tens of inches to 3 ft (about 1 m), visible; rocks of these sizes appear blurry in coarse-resolution imagery. Details of structural condition and rock friction are also made clearer using high-resolution UAV imagery, especially at an oblique view angle that reveals the slope face from the shadow zone sometimes observed from the vertical view angle (Figure 3).

### Yearly Reviews and Updates (RHRS Step 6)

Repeat remote sensing acquisitions allow for the ability to calculate and monitor changes in slope geometry and displacement rates. A previous assessment of overall slope displacements across the railroad corridor was performed using Persistent Scatterer Interferometry and Distributed Scatterer Interferometry (PSI and DSI, respectively), an InSAR stacking technique using radar images acquired via satellites, developed by Bouali et al. (2016). In the case of a rural setting such as this railroad corridor, InSAR is capable of measuring displacement rates for a larger area, such as the general trend of slope movements over long periods of time (which may aid in potential landslide detection), compared to smaller areas, because output data can be spatially limited and detailed measurements may be lacking. Therefore, remote sensing techniques that provide high spatial data densities, such as LiDAR and optical photogrammetry, are preferred for monitoring complex and detailed changes within a slope.

Since Slope 1 was considered the most hazardous slope based on preliminary and detailed slope ratings (Tables 2 through 6), LiDAR point-cloud data were acquired during each summer from 2011 to 2014 using a RIEGL LMS-Z210ii instrument, acquiring data at an angular resolution of 0.005° and an accuracy of around 3 cm. A detailed quantification of slope deformation was performed using a technique called “change detection,” wherein three-dimensional point clouds from two acquisitions are geometrically compared; a change, or difference, in point-cloud location indicates the occurrence of measurable displacement. Figure 4 shows the surficial changes occurring between 2011 and 2014, mapped on a three-dimensional digital elevation model (3D DEM) of Slope 1. Blue regions (negative change) show material loss and red regions (positive change) show material accumulation. Six individual rock falls...
occurred on the Slope 1 face between 2011 and 2014 (numbered values in Figure 4), with substantial accumulation of material occurring at the central toe region.

Detailed change detection measurements, along with similar techniques termed SfM, which utilize optical photogrammetry to create three-dimensional point clouds (Westoby et al., 2012), and InSAR can assist in the yearly review process. By capitalizing on advancements in remote sensing technologies—such as increased spatial and temporal resolution, wider variety of view angles, more accurate sensors, and a growing variety of clever data processing techniques—transportation agencies can monitor potentially hazardous slopes with a more robust, efficient, and time-effective RHRS approach.

Additional Discussion

The three RHRS steps discussed in detail were Preliminary Slope Rating (Step 2), Detailed Slope Rating (Step 3), and Yearly Review and Update (Step 6). Remote sensing techniques can also play a secondary role in information collection and analyses in the other three RHRS steps. Step 1, Slope Inventory, can be aided by analyzing DEMs generated from satellite/aerial optical or radar images (e.g., NASA’s Shuttle Radar Topography Mission, German Aerospace Center Terra SAR-X and TanDEM-X, etc.). DEMs can assist in cataloging and digitizing the spatial extent of slopes adjacent to the transportation corridor. Step 4, Project Design and Cost Estimate, may benefit from detailed models derived from three-dimensional point clouds obtained from optical photogrammetry or LiDAR techniques. These models can help determine remediation designs and techniques that need to be constructed. Step 5, Project Identification and Development, is a management step that utilizes information gained from Steps 1 through 4 to determine necessary remediation projects for choice slopes. Pierson and Van Vickle (1993) provide four project identification methods: (1) score—priority given to slopes with highest detailed slope rating; (2) ratio—priority given to slopes with greatest score-to-cost ratio; (3) remedial—slopes with similar designs can be placed in a single project, which will alter slope prioritization; and (4) proximity—slopes closest to rockfall sites are given highest priority. Each of these project identification methods can use remote sensing data, directly or indirectly. Thus, remote sensing techniques are practical supplementary tools to the traditional field-based approach for RHRS.

Using remote sensing has its advantages and limitations. Advantages include the following:
is much simpler. If, however, a transportation agency is tasked with monitoring a transportation corridor or an entire transportation network (e.g., local, regional, state-wide), then a remote sensing–based RHRS approach, using high-resolution optical imagery, may be preferable. For the remote sensing–based RHRS estimation, high-resolution imagery acquired from different view angles is critical. The spatial resolution and view angles obtained from satellite imagery are coarser, more limited, and often result in significant underestimation of preliminary and detailed slope rating scores. However, an approach integrating rapidly deployable UAV platforms with high-resolution optical sensors and high-resolution terrestrial LiDAR provides a readily available tool set for collecting imagery that can be used for RHRS interpretation. UAV- and LiDAR-based data collections provide much higher spatial resolution and can easily obtain multiple view angles compared to satellite-based data. Detailed slope rating scores from UAV data show promise in terms of their use as an alternate approach for field-based RHRS measurements when monitoring transportation corridors. In addition, imagery collected using UAV will provide a more methodical documentation of the site condition for the transportation agency, compared to field-based data collection. Coupled with other remote sensing techniques (e.g., InSAR and optical photogrammetry), transportation agencies would benefit from a supplementary and complimentary remote sensing RHRS approach.

CONCLUSIONS

RHRS is a procedure developed by Brawner and Wyllie (1975) and further expanded by geological engineers and transportation agencies (Wyllie et al., 1979; Wyllie, 1980, 1987; Pierson, 1991, 1992; Pierson and Van Vickle, 1993; and Brawner, 1994), to analyze slopes adjacent to transportation corridors and to prioritize those most likely to experience damaging rockfalls. The traditional RHRS approach is to use personnel to acquire field-based measurements, especially for Steps 1 through 3. Video logs are also commonly used for data analysis in Step 3 and for slope monitoring in Step 6. The purpose of this study, however, is to show the benefits of remote sensing data acquisition (optical satellite imagery, optical UAV imagery, and terrestrial LiDAR) and analyses for a more robust, efficient, and time-effective RHRS approach. Other remote sensing techniques, such as optical photogrammetry and InSAR, are also discussed and referenced. These remote sensing methods have a place as a supplemental data acquisition approach alongside the traditional field-based approach.

Observations from remote sensing imagery were compared to field-based observations (used as the
baseline) for the preliminary and detailed slope rating steps. Fourteen slopes along a railroad corridor in southeastern Nevada were studied. In general, observations using optical satellite imagery provided an understimation of preliminary and detailed slope ratings. This is most likely due to the coarse-resolution imagery used (meter-scale). It was therefore concluded that high-resolution imagery is a requirement because consistent rating score underestimations may potentially lead to undetected future rockfall events, which is unacceptable. UAV imagery were obtained for Slopes 1 and 2 only because of field time limitations. When using higher resolution imagery acquired from the UAV (centimeter-scale), an overestimation of preliminary and detailed slope rating scores occurred (when compared to satellite- and field-based approaches). This result is likely due to the combination of high resolution (small slopes features and characteristics that can be observed) and various view angles (more information about the top of the slope is available) when compared to field-based approaches limited to ground level.

Terrestrial LiDAR change detection successfully monitored rockfall events on Slope 1. Two threedimensional point clouds, which map the location of the slope face surface, were geometrically differenced to calculate the amount of surface change (slope deformation) that occurred between the summers of 2011 and 2014. Evidence of surficial displacement includes six locations of rock mass loss and an overall accumulation of material at the slope toe. Displacements of up to 2 to 3 m in both directions (toward and away from the LiDAR sensor) were measured over the 3-year span. Change detection, and other similar techniques (e.g., SfM, InSAR stacking), enable measurements of dynamic events that occur rapidly (e.g., rockfalls) or very slowly (e.g., landslide creep) over any length of time (e.g., daily, monthly, annually, etc.).

Every slope within or adjacent to a transportation corridor has the potential to pose hazards that may affect the performance and quality of transportation assets and the safety of its users. The traditional RHRS procedure attempts to identify and prioritize the most hazardous slopes through a robust field-based rating system. The use of remote sensing techniques has proved beneficial by providing more information, expanding the observable study area, archiving historical data sets, and allowing for detailed analysis otherwise unavailable to field crews. By combining remote sensing techniques with traditional field-based approaches, transportation agencies can build a more robust, efficient, and time-effective RHRS procedure that can assist in the achievement of slope lifecycle performance goals along an entire transportation network.

ACKNOWLEDGMENTS

This project was funded by the U.S. Department of Transportation (USDOT) through the Office of the Assistant Secretary for Research and Technology (Cooperative Agreement No. RITARS-14-H-MTU). The authors would like to express their utmost gratitude to the railroad company that allowed us access to the study site and to the on-site employees who kept us safe. The authors would also like to thank Michigan Tech Research Institute’s Richard Dobson, Ben Hart, and David Dean and Michigan Technological University’s Zachary Champion for their contributions to field data acquisition and the six Michigan Technological University participants for providing input with the RHRS survey. Additional thanks are extended to the organizations that provided the background images used in this research study, specifically the U.S. Geological Survey, the National Aeronautics and Space Administration, Google, and Digital Globe.

DISCLAIMER

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