Factors Contributing to Rockfall Occurrence and the Associated Risk in Rockville, Utah

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Abstract

The east-west trending, south-facing slope in Rockville, Washington County, Utah is well known for experiencing large-size rockfalls, including the fatal rockfall of December 2013 that destroyed a home and killed two people. The stratigraphic units present in the area include the well-indurated, Upper Triassic, Shinarump Conglomerate Member (cliff-forming unit) of the Chinle Formation that caps the less-resistant, Lower Triassic, Moenkopi Formation (slope-forming unit). We performed a detailed study to investigate the factors that contribute to rockfall occurrence and the associated risk in the Rockville area. To accomplish this objective, we selected four representative sites along the slope and a few supplemental sites for additional data. The results of our study indicate that the main factors contributing to rockfall occurrence include unfavorable orientation of discontinuities, differential weathering resulting in undercutting, and regional climate (infrequent, high precipitation events; freeze-thaw cycles) whereas those contributing to rockfall risk include high slopes, presence of gullies that channelize rockfall debris, and proximity of homes to the toe of the slope. The results also show that the western portion of the study area poses the highest risk due to the presence of higher slopes, larger exposure of the Shnabkaib Member (the weaker rock unit) resulting in undercutting, higher number of deep gullies, and the higher number of residences closer to the slope toe.

1 Introduction

The town of Rockville in Washington County, Utah (Fig. 1), is known for frequent, large, hazardous rockfalls. There have been at least six large rockfalls within the past 38 years (1976; October, 2001; October, 2002; spring, 2007; February, 2010; November, 2010), with five of the six occurring in the past 14 years (Knudsen 2011). The rockfall on December 12, 2013, destroyed a house (Fig. 2) and resulted in the deaths of its two inhabitants (Dalrymple and Piper 2013; Mabbutt 2013; Lund et al. 2014). The rock mass, weighing approximately 2450 tonne fell from a 122 m high slope.

The stratigraphic units present in the area include the well-indurated Upper Triassic Shinarump Conglomerate Member (cliff-forming unit) of the Chinle Formation that caps the less-resistant Lower Triassic Moenkopi Formation (slope-forming unit). The Shinarump Conglomerate Member is 18–41 m thick, dips 1° to 2° to the east, and contains widely spaced vertical joints (Knudsen 2011). It is a medium- to coarse-grained pebbly sandstone and conglomerate. The Moenkopi Formation is a reddish-orange to reddish-brown siltstone, mudstone, and fine-grained sandstone. It generally thins to the northeast from about 122–183 m thick, west of St. George, to 61–85 m thick in the Zion National Park area (Utah Geological Survey 2013). The Moenkopi Formation slopes are covered with thick (14 m) talus deposits, derived from the Shinarump Conglomerate (Knudsen 2011). The Moenkopi Formation consists of two members: the Upper Red member and the Shnabkaib Member (Fig. 3). The Upper Red member consists of shallow marine and mudflat deposits whereas the Shnabkaib Member represents a sabkha environment (Graham 2006). An unconformity is present between the Chinle Formation and the

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Fig. 1 Location of Rockville in Washington County, Utah
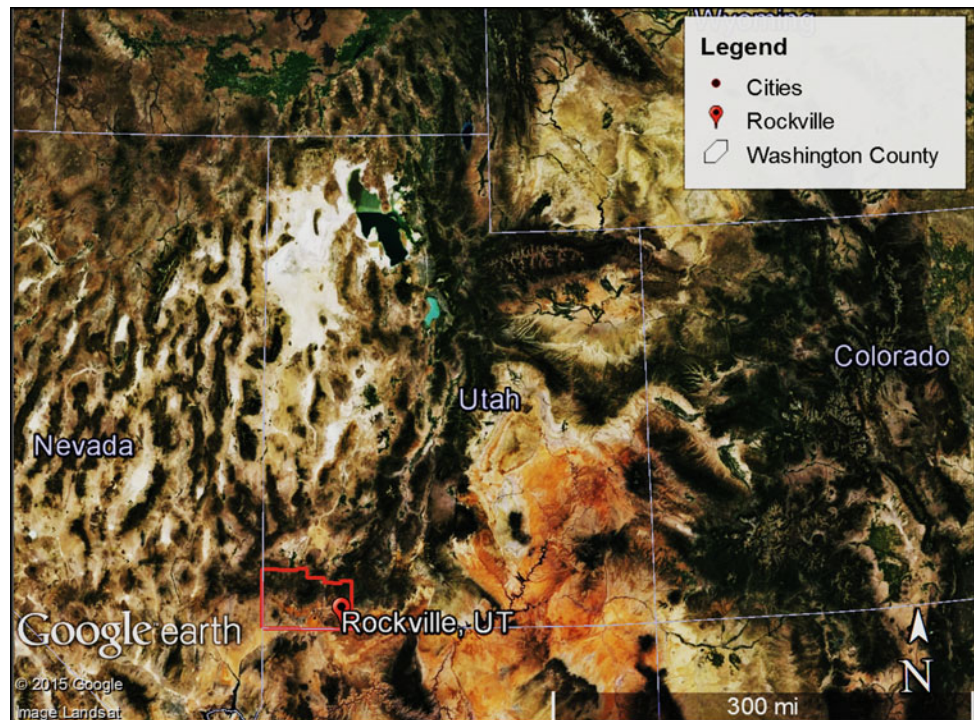
Fig. 2 The house after the December, 2013 rockfall (Lund et al. 2014)

Moenkopi Formation. A stratigraphic cross-section of the study area can be found in Jacklitch et al. (2018).

The purpose of this research was to evaluate the factors that contribute to rockfall occurrence and evaluate the potential risk from rockfalls to residences in Rockville, Utah.

2 Methods

We selected four primary sites along the Rockville slope for detailed investigations and several supplementary sites for additional data. Figure 4 shows the locations of the selected

Fig. 3 An overview of the stratigraphy of Rockville slope near the fatal rockfall site

Fig. 4 Location of the four primary sites and the supplemental data sites on a USGS topographic map overlay (Google Earth). *Note* 1 mile = 1.6 km
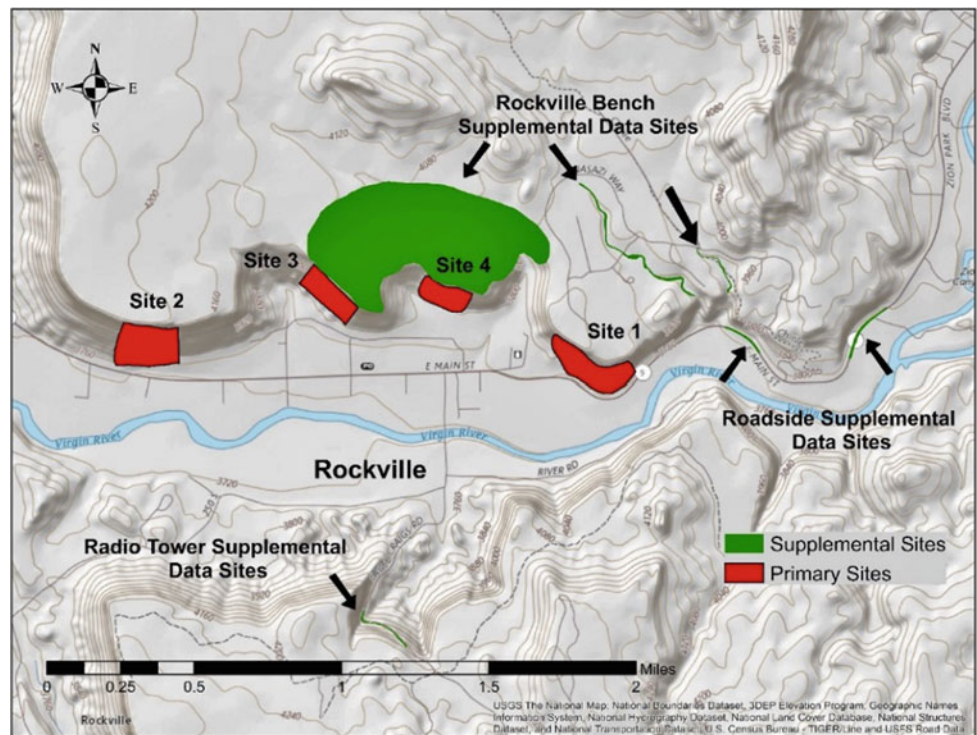
sites. We conducted field investigations to evaluate factors contributing to rockfall occurrence and rockfall risk as well as to determine slope geometry (strike and dip, slope height, slope length), establish slope stratigraphy, collect discontinuity data, evaluate modes of failure, and obtain samples for laboratory testing. For collecting discontinuity data, we used the window mapping and random mapping methods (Wyllie

and Mah 2004) to record the following aspects of discontinuities: geometry, continuity (extent), spacing, aperture, infilling material (if present), surface irregularities, and presence or absence of water. The modes of failure affecting the slopes in Rockville were evaluated using both field observations and results of kinematic analysis. We collected block samples of various rock units for laboratory testing.

The rock blocks were cored in the laboratory to prepare NX-size (54 mm) cores.

We performed laboratory investigations to determine density (mass/volume), basic friction angle, and second-cycle slake durability index values for various rock units comprising the slopes in the study area. We used density and friction angle for rockfall simulations and kinematic analysis, respectively, and slake durability index to evaluate the potential for undercutting of the resistant rock units (Shinarump Conglomerate Member) by the less resistant rock units (Moenkopi Formation). We determined the density values for different rock units by dividing the mass of a core sample from a particular unit by the volume of the sample. We used the Stimpson (1981) method to determine the basic angle of friction. We stacked three cores from each rock unit on a tilting table such that two cores were fixed in place side-by-side and the third core was placed on top, free to slide. The table was tilted until the top core slid over the lower two cores. We measured the tilt angle of the table using a Brunton compass. We used the tilt angle in the following equation to calculate the basic friction angle—$\phi = tan^{-1}(1.155 \tan \alpha)$, where ϕ is the internal angle of friction and α is the tilt angle (Stimpson 1981). We used ASTM method D-4644 (ASTM 2010) to determine the second cycle slake durability index (Id_2) of the Moenkopi Formation. Six samples collected from two of the sites (four samples from Site 1 and two samples from Site 2) were used for the test.

The data analyses for this study consisted of: (1) stereonet analysis; (2) kinematic analysis; and (3) rockfall analysis. We used Dips software (Rocscience 2014) to perform stereonet and kinematic analyses and RocFall software (Rocscience 2015) to conduct rockfall analysis. The purpose of the stereonet analysis was to determine the principal joint sets. The kinematic analysis was used to evaluate the potential for planar failures, wedge failures, and toppling failures. We used the principal joints, the slope angles, and the basic friction angle for kinematic analysis. The rockfall analysis was conducted to determine the trajectories and the rollout distances of rock blocks of specific sizes. Slope profiles were developed for each of the four sites using USGS topographic maps and aerial imagery from Google Earth and Bing Maps. We entered the slope profiles into RocFall and selected the parameters for the slope material from the suggested values in the RocFall software manual (Rocscience 2015). The parameters included the coefficient of normal restitution, the coefficient of tangential restitution, the dynamic friction coefficient, and the rolling resistance.

In order to calibrate the parameters to ensure accuracy of the model, the parameters were tested with the known block shape, density, mass, and rollout distance of the largest block at the fatal rockfall site. The block shape, density, and mass are the three parameters that can be altered for the rollout distance analysis. As the density remains constant for a given lithology, we altered the block shape and mass at each site to find the combination that yielded the greatest rollout distance. There are 22 shape options available for the general shape of the rock block. Our field observations indicated that rockfall-block sizes and shapes were highly variable. Therefore, in order to accommodate maximum variability, we let the computer program select all 22 shape options. With all 22 shapes selected, 11,000 rock blocks were selected for each run. This provided 500 blocks of each of the 22 block shapes. With the block shape and density fixed, the mass of the block was manually altered for each run until the maximum rollout distance was determined. This process was repeated for all four sites.

3   Results of Field and Laboratory Investigations

The average slope angle is 40° for Sites 1 and 2 and 35° for Sites 3 and 4, slope height ranges from 79 m for Site 1 to 131 m for Site 2, and slope length ranges from 137 m for Site 2 to 457 m for Site 1. The average extent of discontinuities for the Shinarump Conglomerate Member and the Upper Red member, respectively, are 5 and 3 m, average spacing 1.8 and 1.7 m, and average aperture 0.25 and 0.5 cm. Most discontinuities are moderately smooth to moderately rough, have no infilling material, and were dry during the field investigation stage. The Shinarump Conglomerate Member has an average density of 2.27 g/cm^3, and the Upper Red member has an average density of 2.64 g/cm^3. The Id_2 values range from 9% for the weaker units to 97% for the stronger units.

4   Factors Contributing to Rockfall Occurrence

Field observations revealed that factors contributing to rockfall occurrence in the Rockville area include discontinuities, differential weathering, and climate.

4.1   Discontinuities

Among the various aspects of discontinuities recorded in the field, orientation is the most important factor contributing to rockfalls. If the orientation of discontinuities present at a given site does not indicate the potential for a kinematically possible failure, the other aspects of discontinuities become irrelevant. The primary mode of failure for the Shinarump Member, as indicated by the kinematic analysis, is wedge failures. The potential for wedge failures exists at all four

sites. Planar failures within the Shinarump Member are a possible mode of failure at Site 4 and toppling failures are possible at Sites 2 and 3. Within the Upper Red member, all three modes of failure are possible at Sites 1 and 3. Sites 2 and 4 did not show the potential for any mode of failure within the Upper Red member. This does not mean that a slope failure will not occur in the future within the Upper Red member at these sites as undercutting of the Upper Red member, due to differential weathering, may induce rockfalls or other modes of failure. It should be noted that regardless of the mode of failure, all failures end up as rockfalls because of the high slopes in Rockville.

Continuity (extent) and spacing of discontinuities are other important aspects of discontinuities with respect to rockfall hazard as, together, they define the size of the rock block that may detach and fall. Most discontinuities extended the full thickness of the rock unit. Although the average spacing of the discontinuities is approximately 1.8 m, some blocks were continuous for a lateral distance of as much as 46 m. At many locations, a spacing of 5–9 m was observed. The continuous nature and wide spacing of discontinuities are responsible for the frequent large-size rockfalls in the Rockville area such as that of December 12, 2013.

The majority of the discontinuities at the sites were closed and had little or no aperture; however, some discontinuities were open with nearly 0.3 m of separation. The presence of aperture at some locations contributed to the potential for failures.

Most discontinuities at the study sites were moderately rough to moderately smooth. We observed that the valley stress relief joints were predominately smooth whereas the other discontinuities were moderately rough. With the relatively low roughness of the discontinuities, there is less resistance to failure from the rock-to-rock contact. Because of the low roughness, we believed that adjustments to the basic friction angle, as determined by the Stimpson (1981) method, for use in the kinematic analysis, were not warranted. Using the basic friction angle represented the worst case scenario for the analysis and evaluation of the rockfall hazard.

4.2 Differential Weathering

Results of the slake durability test show that there is a very high potential for differential weathering within the Moenkopi Formation. The weaker units had Id_2 values between 9 and 25% whereas the stronger, more resistant units, had Id_2 values ranging from 94 to 97%. The rock units within the Moenkopi Formation that exhibited the lowest slake durability index values were those that contained lenses and seams of gypsum and were more clayey in nature. The large

difference in slake durability index values between the stronger and weaker rock units within the Moenkopi Formation indicates a high potential for differential weathering and the associated undercutting of stronger rock units by the weaker rock units (Fig. 5). The amount of undercutting between the Shinarump Conglomerate Member and the Moenkopi Formation (Fig. 6) is variable across the study area. The primary factors that contribute to the variability in the potential for undercutting between the two rock units is whether the portion of the Moenkopi Formation unit that is in contact with the Shinarump Conglomerate Member consists of more resistant or less resistant rock, or whether the cream to maroon colored silty mudstone lenses are present (Fig. 7). The silty mudstone lenses that exist beneath the Shinarump Member, throughout the study area, promote differential weathering because of their moderate to low durability ($Id_2 = 69\%$). Within most of the study area, the contact between the Shinarump Conglomerate Member and the Moenkopi Formation is covered with colluvium, protecting it from undercutting. However, the mudstone lenses are not protected by colluvial soil because of continual weathering.

4.3 Climate

The climate seems to be an important factor in contributing to rockfall occurrence in the Rockville area. It played a significant role in the rockfall that occurred on December 12, 2013, and some of the other recorded major rockfalls. During the end of November and the beginning of December, 2013, there was a total of 6.6 cm of precipitation. Within the same period of time, the temperatures fell below freezing at night and rose above freezing during the day. The lowest temperature for the year (−20 °C), and the lowest temperature in a ten year span, occurred three days prior to the incident. Yet, the daily highs were still in the 10–15 °C range. This freeze-thaw activity likely contributes to all rockfalls in the area, including the rock blocks that fell on December 12, 2013.

5 Factors Contributing to Rockfall Risk

Field observations indicated that the following factors contribute to rockfall risk:

5.1 Slope Height

Slope height adds to rockfall occurrence and the associated risk in two ways. A higher slope is typically less stable as it

Fig. 5 Undercutting of the cliff-forming resistant rock unit within the Upper Red member of the Moenkopi Formation by the less resistant slope-forming rock unit at Site 1

Fig. 6 Undercutting of the Shinarump Conglomerate Member by the Moenkopi Formation between Site 3 and Site 4, resulting in potentially unstable blocks of the Shinarump Conglomerate Member

Fig. 7 One of the lenses of red to gray mudstone that separates the Shinarump Conglomerate Member from the Moenkopi Formation at several locations

cannot support its own mass. Also, the material that falls from higher slopes gains more momentum as it travels down the slope. This, in turn, creates a greater risk for any object in the pathway of the travelling rock mass. For the Rockville slope, the height decreases from 131 m in the west to 61 m in the east. This suggests a higher potential for rockfall occurrence as well as a higher degree of rockfall risk for the western portion of the study area.

5.2 Gullies

While the gullies do not induce rockfalls, they can channelize the rockfalls and debris released from the slope. Therefore, a structure built near the mouth of a gully would have a higher risk of damage from rockfalls. Figure 8 shows examples of gullies at the field sites. Gullies, some of which are fairly deep (>1.8 m), are most prevalent within the western slope, but become less extensive toward the east. This is probably because the Shnabkaib member (the weaker rock unit) is below the ground surface in the eastern portion of the study area.

5.3 Proximity of Homes to Slope Toe

Most homes in the town of Rockville are located very close to the slope toe (Fig. 3). This obviously increases the risk from rockfalls.

In summary, field observations revealed that the western portion of the study area poses the highest risk from rockfalls due to the presence of higher slopes, higher number of deep gullies, and higher number of residences closer to the slope toe.

6 Modified Rockfall Hazard Rating System for Rockville

The Oregon Department of Transportation (ODOT) rockfall hazard rating system (RHRS) (Pierson 1991) is frequently used to evaluate rockfall hazard. However, the original system was developed for slopes under 33 m in height and rock block sizes under 1.1 m.

Considering the size of the blocks and the height of the slopes in the study area, the ODOT RHRS cannot be used effectively to evaluate the hazard (risk) for the Rockville slopes. Therefore a modified version of RHRS was developed for Rockville that focusses on the risk associated with a rockfall (i.e. the term "hazard" is used here as a synonym for "risk"). The modifications included: "Roadway" was changed to "House," "Annual Maintenance Frequency" was changed to "Annual Frequency", and "Average Daily Traffic" was changed to "Potential for Property Damage/Injury or Fatality". The "Potential for Property Damage/Injury or Fatality" evaluates the possible damage to facilities that are within the rollout distance, as well as the possibility that an injury or fatality may

(a)

(b)

(c)
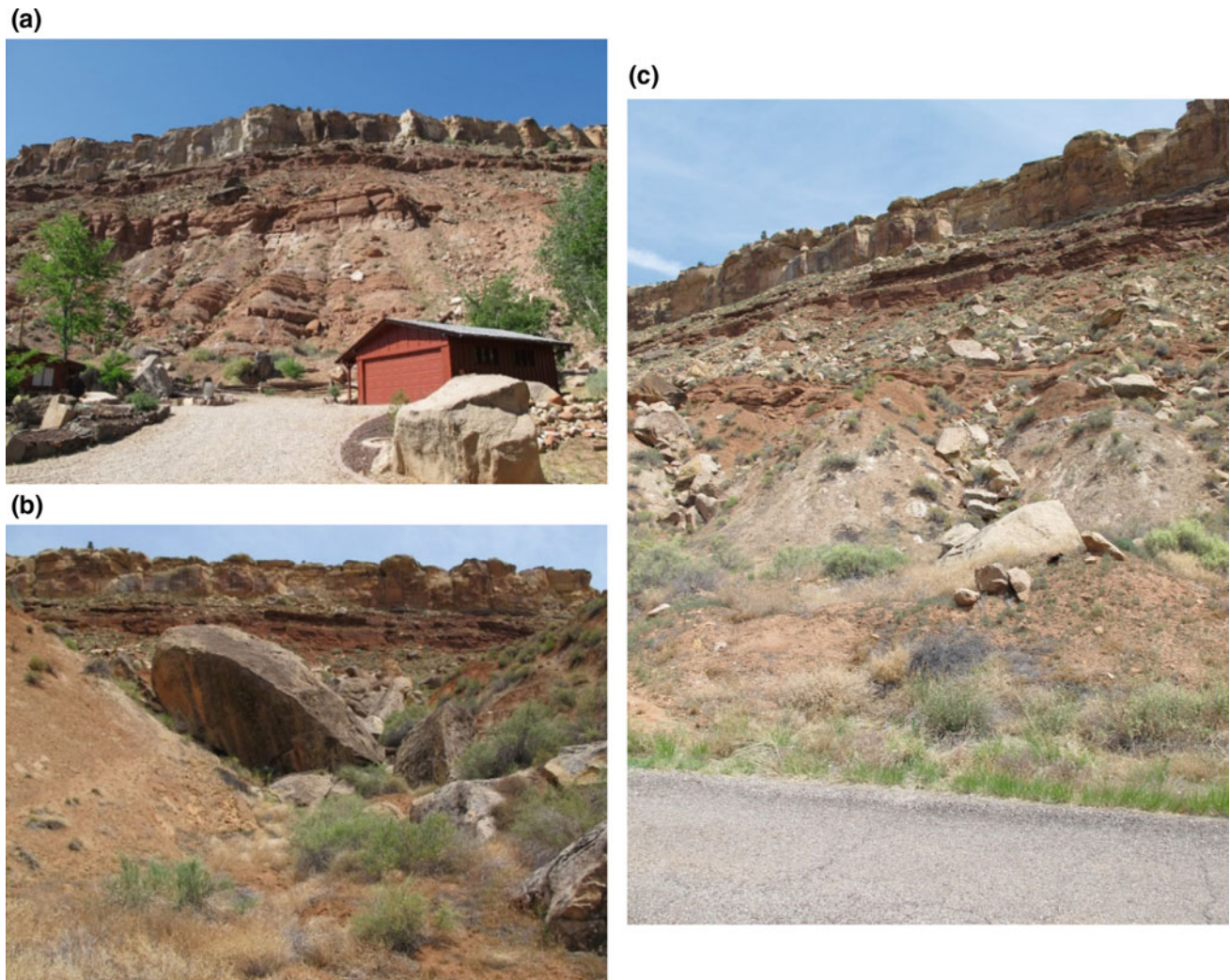
Fig. 8 **a** Gullies at Site 2 with varying sizes of rock blocks; **b** gullies near the base of the slope at Site 3 with large rock blocks; and **c** a large gully at Site 4 with large rock blocks

Table 1 Results of the modified ODOT RHRS for the four study sites

Factor	Site 1	Site 2	Site 3	Site 4
Failure type/hazard	9	100	100	27
House impact	3	81	27	27
Annual frequency	25	25	25	25
Potential for property damage/injury or fatality	30	100	100	100
Accident history	3	100	9	9
Sum	70	406	261	188
Rating (%)	14	81	52	38

occur. In the modified system, the scoring method is the same as the initial ODOT RHRS, with low values representing a low hazard potential and high numbers representing a high hazard potential. A high hazard ranges from 100 to 66%, a moderate hazard ranges from 65 to 33%, and a low hazard ranges from 32 to 0%. The percentages are derived by dividing the score of the slope by the total possible score of 500 (a maximum of 100 for each of the five factors). Table 1 shows the results of the modified version of the RHRS for the four Rockville sites, with Site 2 exhibiting the highest risk and Site 1 the lowest risk from rockfalls.
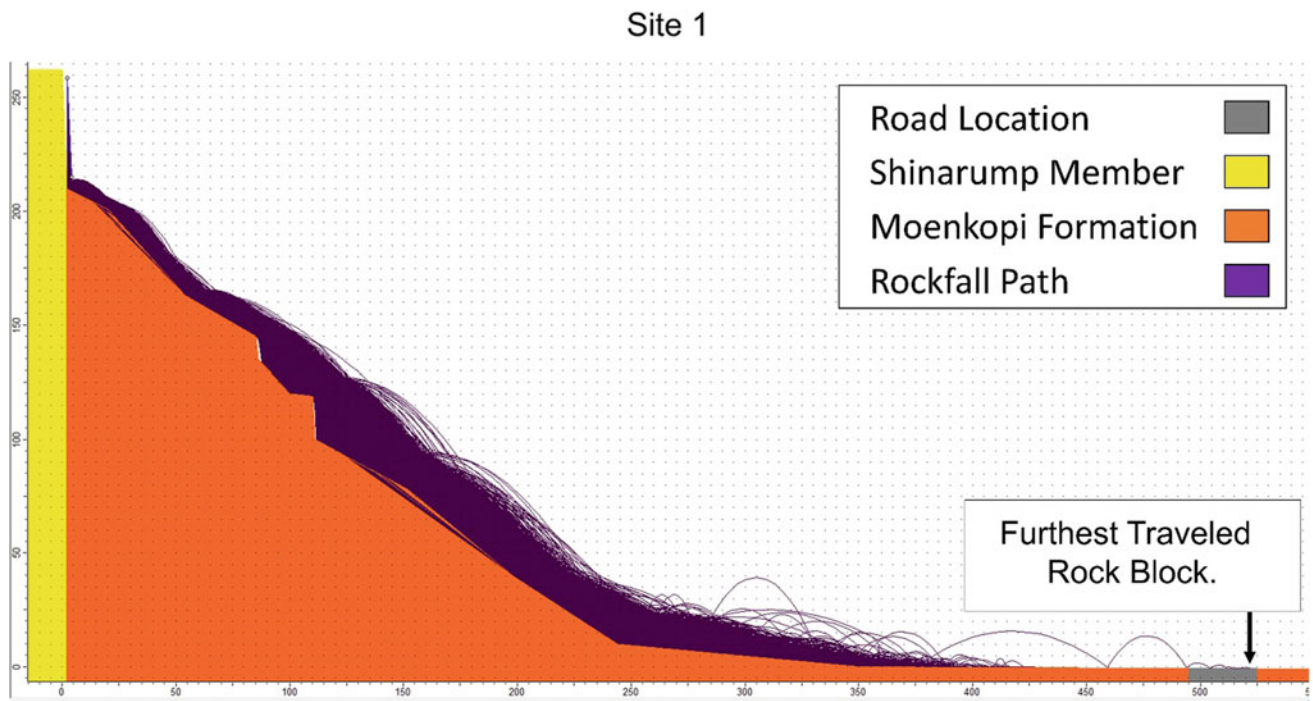
Fig. 9 Rockfall simulation plot for Site 1 using RocFall software (Rocscience 2015). The rock block weighed 41 kg. After 11,000 simulated rockfalls with variable random block sizes and initiation points along the face of the Shinarump Conglomerate Member, the furthest rollout distance from the point of release was 159 m. This distance represents the furthest distance a rock block can travel at Site 1 for the various block sizes tested

7 Rockfall Simulations and Rollout Distances

Using RocFall software (Rocscience 2015), rockfall rollout distances were determined for all four sites. Figure 9 shows an example of such analysis for Site 1. The analysis indicated that the rollout distances for Sites 1, 2, 3, and 4 were 159, 253, 167, and 154 m, respectively. These rollout distances were used to establish the hazardous zones for different portions of the Rockville slope. As long as homes are located within these rollout distances, they are subject to rockfall hazard.

8 Conclusions

The conclusions of this study can be summarized as follows:

1. The factors contributing to rockfall occurrence in the Rockville, Utah, area include unfavorably oriented discontinuities, differential weathering, and climate whereas the factors contributing to risk associated with rockfalls include slope height, gullies, and proximity of homes to toe slope.

2. According to the modified RHRS, three categories of rockfall hazard or risk can be used for the Rockville area with the following scores: high hazard—100 to 66%; moderate hazard—65 to 33%; and low hazard—32 to 0%. Site 2 falls in the high hazard category, Sites 3 and 4 in the medium hazard category, and Site 1 in the low hazard category.

3. The rollout distances for the four sites range from 154 to 253 m. Any current and future homes built within 253 m of the slope toe are exposed to potential risk from rockfalls. However, the extent of risk lessens from the western toward the eastern part of the slope.

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