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ROCK-FALL HAZARD ASSESSMENT OF THE ASPEN FOREST TRAIL, NAVAJO NATIONAL MONUMENT, ARIZONA

By

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Introduction

The National Park Service (NPS) requested the U.S. Geological Survey (USGS) to assess the stability of a section of the Aspen Forest Trail to Betatakin Ruins, Navajo National Monument, Arizona, and to discuss methods of remediation and options for reopening the trail. This report includes a description and analysis of the discontinuities that affect slope stability along the trail and recommendations for access to Betatakin Ruins in consideration of the rock-fall hazards.

The trail, constructed in 1963, has many steep switchbacks at the head of Betatakin canyon and a short constructed overhung section along the southern side of the canyon (Fig. 1). The trail has experienced rock falls beginning after construction in 1963 (Frank Osterwald, written commun. 4/28/82), most seriously in 1982 after two rock falls (3/18-25/82; 12/8/82) blocked the trail in the steep overhung section just below the locked gate. The first rock fall exceeded some 9.5 tons and the second was estimated at 200-300 tons. Since April of 1982 the trail has remained closed to the public. In early 1983 (sometime during February to March) another large rock fall occurred slightly further down the trail that covered the trail and sent rocky debris to the valley floor near Saucer Cave (John Laughter, pers. commun, 6/22/00). The remains of this 1983 rock fall still cover about a 40-foot wide section of the trail.

Fig. 1- Steep, overhung section of Aspen Forest Trail to Betatakin ruins.

In 1985 the NPS contracted Lachel Hansen & Associates, Inc. to investigate the stability of the trail, analyze methods for slope stabilization, and suggest other design alternatives for the trail. The report by Lachel Hansen & Associates (1985) identified seven alternatives for the trail of which four were evaluated for preliminary design and cost estimates. The NPS selected the least expensive of these alternatives and the one that exposed visitors to the least risk; it utilized an alternate route of Tsegi Point Road for access to the Betatakin ruins.

Hazard Assessment of Aspen Forest Trail

The stability of the Aspen Forest trail at the head of Betatakin Canyon is controlled by several geologic factors. The Navajo Sandstone bedrock, weakly cemented by calcite and iron, is strong enough in places on the Colorado Plateau to form steep-sided canyons. The head of Betatakin Canyon, through which the Aspen Forest Trail passes, is very steep and represents an actively eroding canyon that is slowly advancing westward. The density and orientation of joints, bedding planes, and other discontinuities as well as their properties affect the quality or strength of the rock mass, which influences the stability of the rock mass (Fig. 2). The occasional presence of water in discontinuities or infilling of weak materials in the discontinuities creates local zones of weakness. The timing of noted failures during the generally wet winter and spring periods strongly suggests that water infiltrating the joints plays some part in destabilizing the rock mass.

Fig. 2- Numerous joints near Sta. 38.5 and site of 1982 rock falls along overhung section of Aspen Forest Trail. Arrows denote joint surfaces (J_1, see figure 3) that dip steeply out of the slope.

Depending upon the orientation of the canyon wall above the trail, different discontinuities pose potential stability problems. The canyon-wall orientation makes it possible for rock falls to occur more frequently on the southern, north-facing wall than on the northern, south-facing wall of the canyon.

To assess the relative stability and potential for future rock fall along the section of trail where the above-mentioned rock falls have occurred, we used two methods of analysis. Firstly, a graphical stereonet analysis (Markland, 1972) allows the orientations of joints, bedding planes, and fractures to be analyzed at numerous sites to discriminate which discontinuities are likely to provide failure surfaces for future rock falls. This method compares the orientation of the slope with orientations of rock discontinuities and the internal angle of friction (frictional component of shear strength) of the rock to see which fractures, joints, or bedding planes render the rock mass theoretically unstable. Secondly, an engineering rock classification known as "rock-mass-quality" (Barton et al., 1974; Harp and Noble, 1993) was used to assess the fracture characteristics of the rock discontinuities and the relative susceptibility of the rock at numerous sites along the failure-prone section of trail.

Stereonet Analysis-

We measured the direction and amount of dip of 58 planar discontinuities along a steep section of about 800 feet of the Aspen Forest Trail (between Sta. 14 and Sta. 47; station locations are referenced to a survey by Lachel Hansen & Associates, 1985). Based on these measurements we distinguished bedding B and two major joint sets, J_1 and J_2, as well as other isolated random discontinuities (fig. 3).

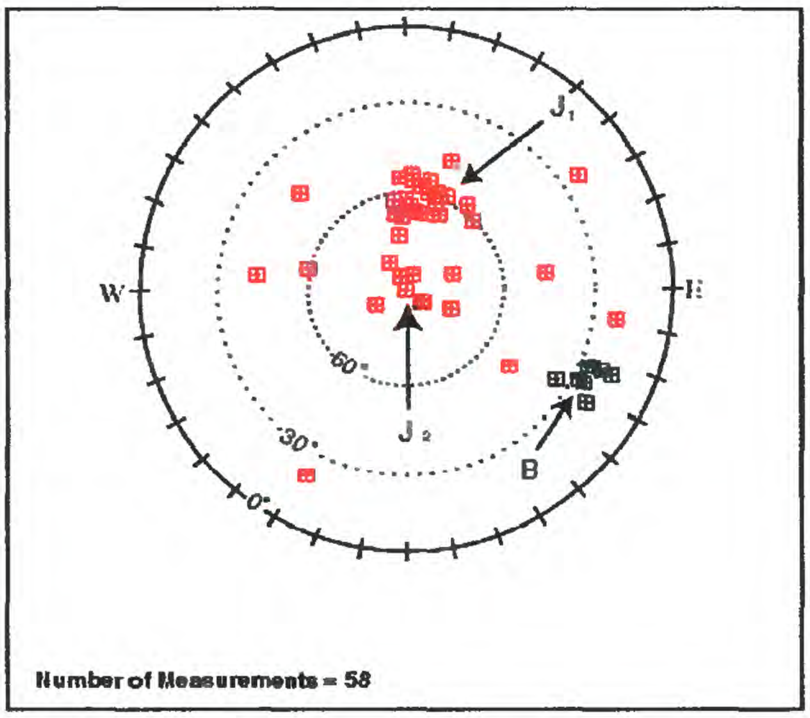


Fig. 3-Equal-area stereonet plot of dip vectors of discontinuities along Aspen Forest Trail between Sta. 14 and Sta. 47. Cluster of measurements in E-SE represent bedding (B) which generally dips about 26 degrees to E-SE. Two other major joint sets are evident, one of which dips about 60 degrees to N (J_1), and the other is near vertical (J_2). The few remaining measurements represent individual, more random joints.

At most sites along this stretch of trail we found from 3 to 5 differently oriented discontinuities of varying persistence, opening, smoothness, roughness and infilling. For analysis within this relatively short stretch of trail we used the entire set of measurements although not every discontinuity was found at each measurement station (Appendix-Table 1). The prominent joint set dipping steeply to the north (J_1 in fig. 3) was commonly closely spaced and filled with caliche, indicating the regular passage of groundwater through the joints.

A Markland (1972) rock-slope stability analysis was used to assess the potential for planar or wedge sliding along discontinuities at various stations along the trail using the ROCKPACK (Watts, 1997) software package. Markland plots (fig. 4) show the discontinuities (bedding and joints) in relation to potential wedge and planar sliding surfaces on a lower hemisphere stereonet projection. The slope face is shown as a great circle and friction is represented by an interior circle. A representative value of 35 degrees was selected for the friction angle along discontinuities in the Navajo Sandstone The results of our analyses were not affected by using friction values within the range of 30-40 degrees. Assuming there is no cohesion along the discontinuities, whenever the dip value of the discontinuity is greater than the friction angle and less than the slope angle, then it will fall within the critical zone (fig. 4) and sliding along the discontinuity is possible.

The point of intersection of two great circles for discontinuities J_1 and J_2 represents the intersection of two planes creating a wedge. If this point falls outside the critical zone (red arrow in fig. 4), then a wedge failure with the two planes is not possible. If this wedge plunges more steeply than the friction angle and less steeply than the dip of the slope face in the direction of the slope face, then the point of intersection falls within the critical zone and sliding of a wedge is possible.

Near the location of the previously mentioned 1982 rock falls (Sta 38.5), a plot of the discontinuities (fig. 4) shows that the cluster of dip vectors of the major N-dipping joint set J_1 nearly enter the critical zone. The original slightly steeper slope (prior to the 1982 rock falls) could have posed a more critical condition for planar sliding than that at present.

To illustrate the effect of a slight variation in the direction of the cut face on slope stability, we examined Markland test plots for Stations 29 and Sta. 33 shown in Fig. 5. In this section of the trail immediately upslope of the gate, the N-dipping joint set J_1 daylights in the slope face, shown as the cluster of points inside the critical zone, thus creating a potential for planar sliding. The intersection of great circles within the critical zone (red arrows in fig. 5) show that conditions are favorable for wedge failures formed by intersection of joint set J_1 and other isolated joints. The conditions are similarly favorable for planar sliding between Sta. 23 and 29.

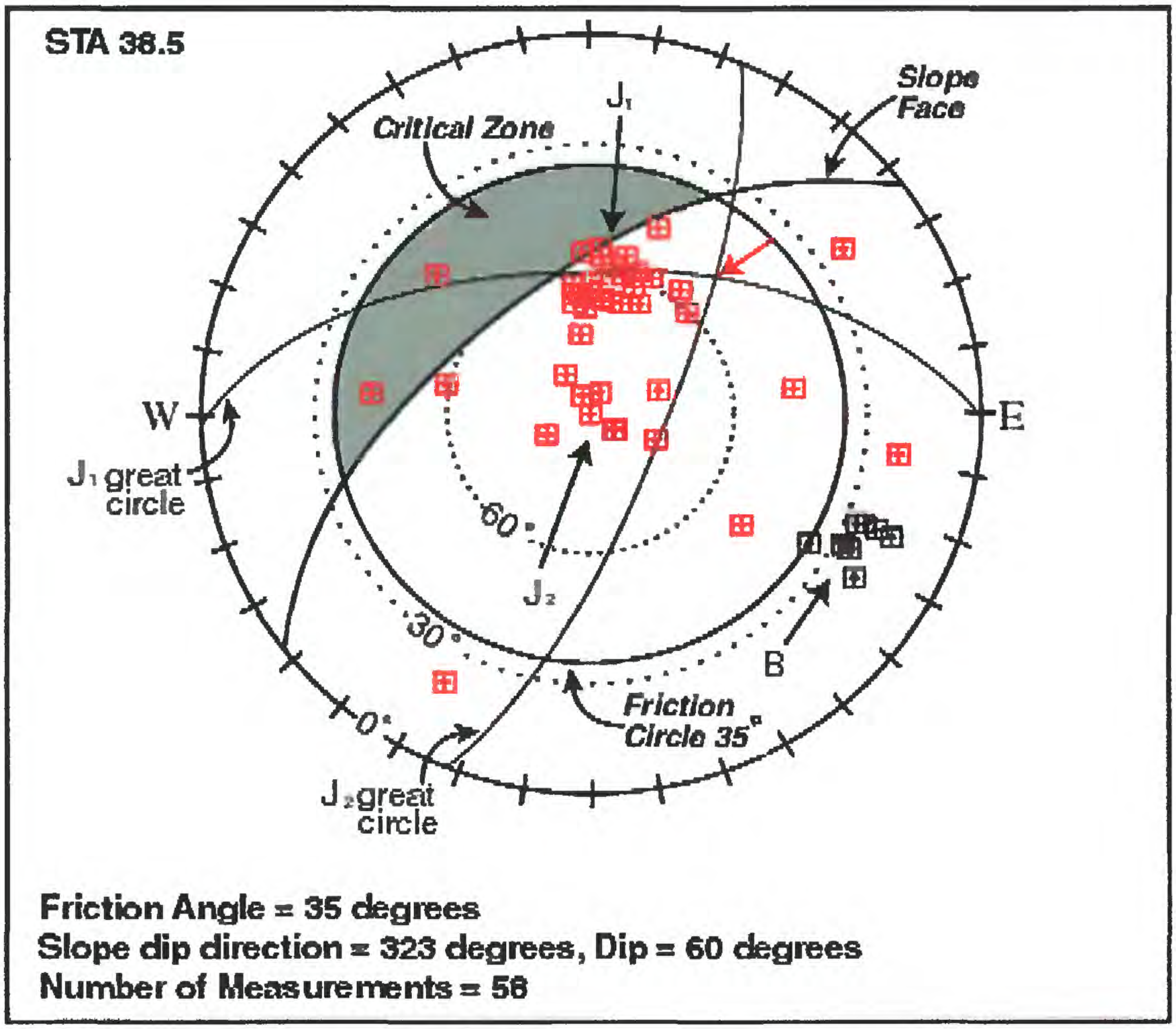
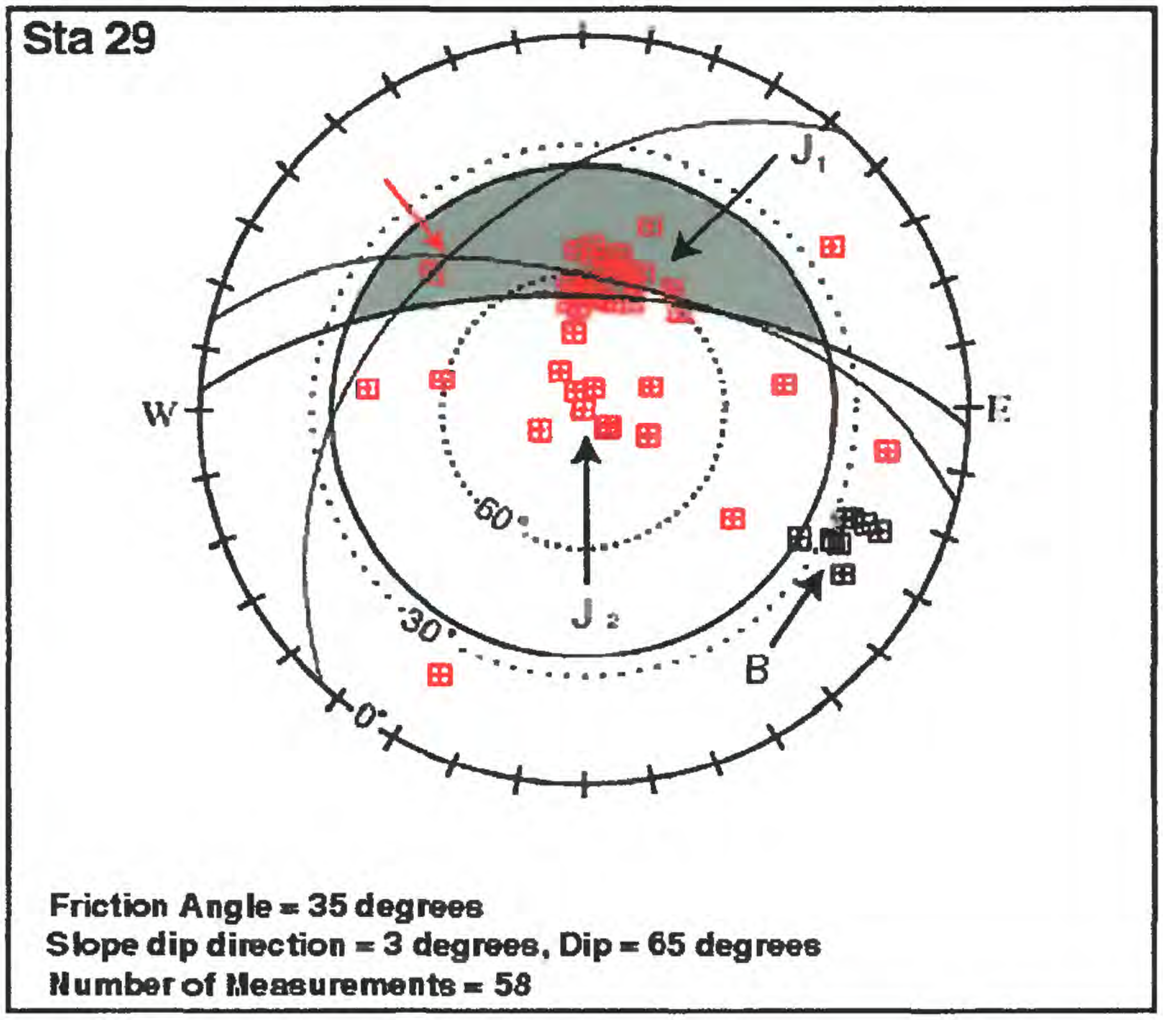


Fig. 4-Markland test plots for planar and wedge failures. Slope face, friction circle, and critical zone for sliding failure are indicated. Red arrow indicating intersection of great circles for joint sets J_1 and J_2 outside of critical zone precludes wedge failure of these discontinuities.



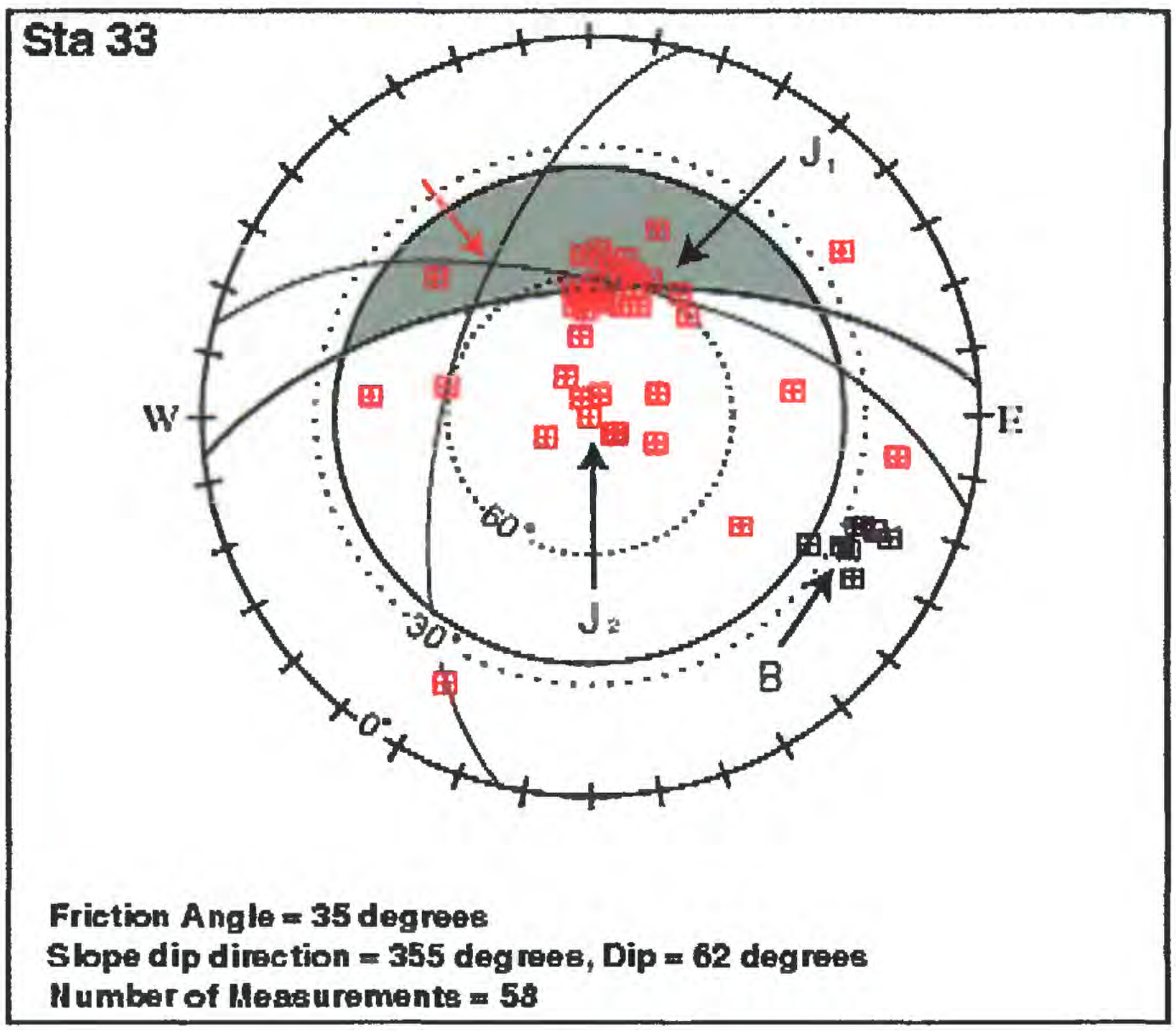


Fig.5-Markland test plots for planar and wedge failures. Red arrows to intersections of great circles for discontinuity J_1 and isolated joints in critical zone indicate potential for wedge failures.

Rock-Mass-Quality Analysis-

The relative susceptibility of the rock slopes at the head of Betatakin Canyon to failure as rock falls or rock slides was evaluated using an engineering criteria devised by Harp and Noble (1993) that uses the characteristics of rock fractures, joints, and bedding to quantify its potential for failure under seismic conditions. Although infiltration of water and development of water cleft pressures in discontinuities probably triggered the recent failures, we used the method of Harp and Noble (1993) as an approximation of slope stability under nonseismic conditions. The calculation of "Rock-Mass-Quality" (Q) is accomplished by comparing the discontinuities of the rock slope in question with descriptive tables (Harp and Noble, 1993) with numerical ratings for six fracture characteristics: J_v- total number of joints per cubic meter, J_n- number of joints sets in the rock mass, J_r- joint roughness, J_a- alteration of the joint surface by weathering or infilling of minerals, J_w- water flow from joints (assumed to be 1.0 at most surface outcrops where the rock face is dry), and AF- aperture or "openness" of joints. With numbers for each of these factors, values of Q are given by the following equation.

$$Q = \left[\frac{115 - 3.3J_v}{J_n}\right]\left[\frac{J_r}{J_a}\right]\left[\frac{J_w}{AF}\right] \qquad \text{Eq. 1}$$

At specific times of year when water flows from joints, the calculated values of Q would be lower than we have determined. A more complete description of this method to evaluate rock-slope susceptibility is available in Harp and Noble (1993).

A low value for Q, for instance, ranging from 0.001-0.09 would indicate a high degree of susceptibility, while high numerical values within the range of 10.0-1,226 (the theoretical maximum) indicate rock slopes of low susceptibility. Moderate susceptibilities are indicated by the middle numerical ranges (1.0-9.9) and can be divided into as many categories as are useful.

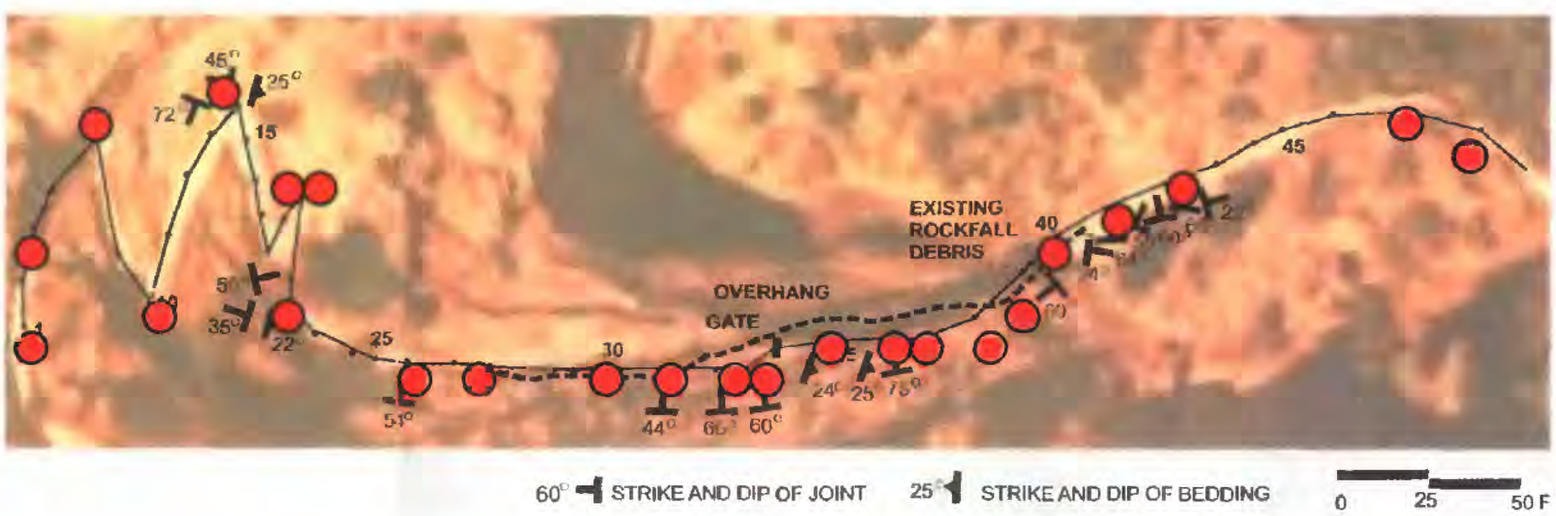


Figure 6. Plot of survey stations (shown as small black numbered dots along solid line) from west (Sta. 1 at left) to east (Sta. 48 at right) along Aspen Forest Trail by Lachel Hansen & Associates (1985). Larger red dots denote sites of measured Q-values. Dashed line indicates position of rock cliff above trail. Strike and dip measurements are from Lachel Hansen & Associates (1985).

Application to Aspen Forest Trail-

The above method was used to evaluate the susceptibility of rock-slope sections of the Aspen Forest Trail at the head of Betatakin Canyon. Twenty-four Q-values (Appendix-Table 2) were calculated at points along the Aspen Forest Trail between points 1 and 48 of the survey done by Lachel Hansen & Associates (1985, fig. 6). The numerical Q-values at each of the sites with respect to the survey points are shown in figure 7.

The bar graph in figure 7 shows the relative susceptibilities of the rock adjacent to the trail from survey points 1 to 48. As can be seen in the figure, the lowest values, and therefore the highest susceptibilities, are found adjacent to points 35 to 40 along the overhung section of the trail and adjacent to points 2.4 to 5 above this section. The rock along these two sections of trail would be rated as "high susceptibility" due to the fact that the numerical values are less than 0.1 for most of the points in these sections. The remainder of the sites qualify as "moderate susceptibility". None of the rock where Q-values were calculated can be considered as "low susceptibility." Compared to much of the Navajo Sandstone outcrops in this area, the Q-values along the measured section of trail are relatively low. Massive outcrops of Navajo Sandstone can have quite high Q-values that place it well within the "low susceptibility" range.

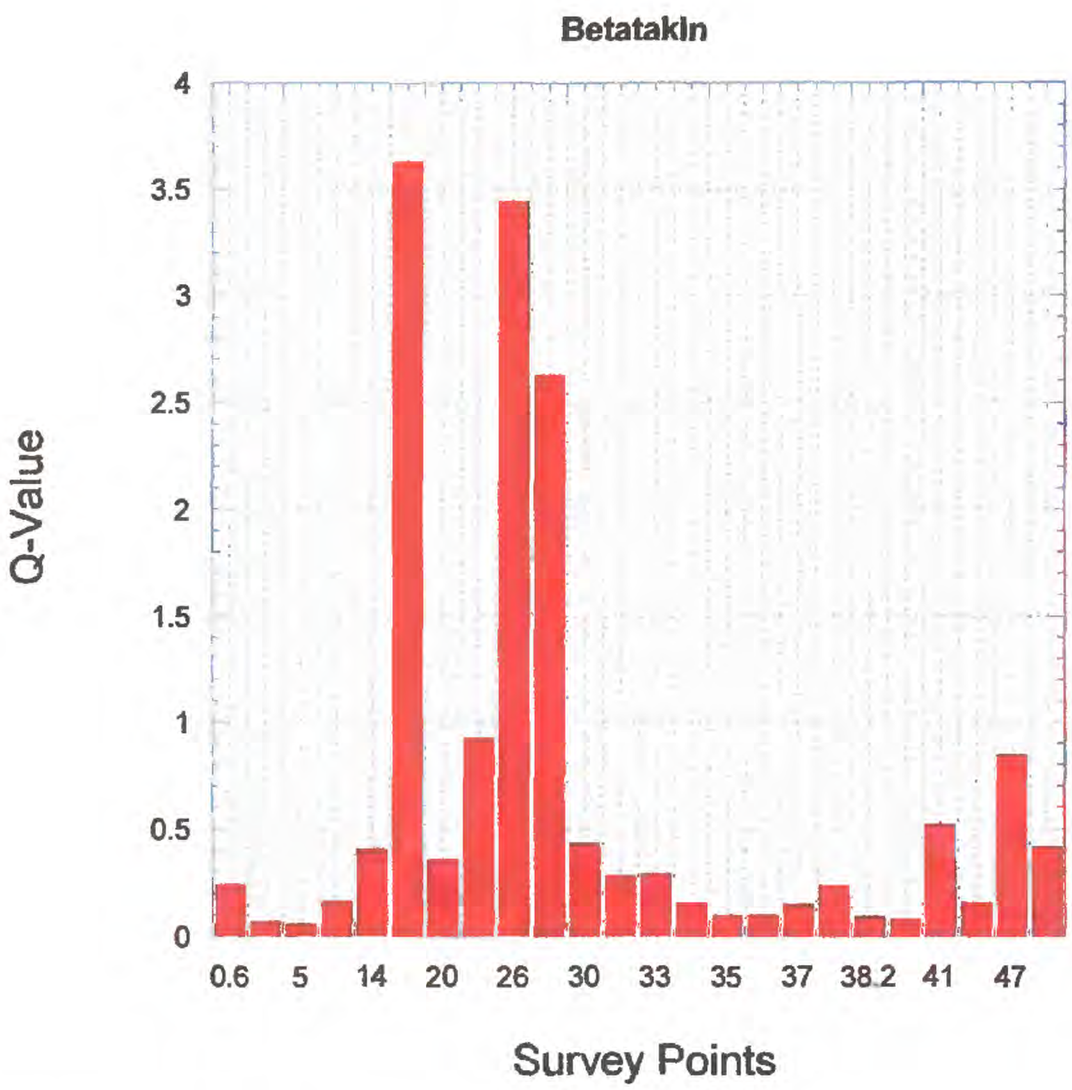


Figure 7. Numerical values of Rock Mass Quality with respect to survey points of Lachel Hansen & Associates (1985).

Present Hazard to Public

With Q-values that place the rock within the high to moderate susceptibility categories for those sections where the 1982 rock falls occurred and another section above near points 22 and 23, the hazard to the public would also be moderate to high for exposure to rock falls if the trail were opened in its present condition. In addition, there are numerous rock masses located on the cliffs above the trail that appear to be in a condition of marginal stability. Many of these are wedges of rock attached to the cliff across side joints but with no visible support along their bases. Some of these rock masses have apparently moved downward along the side joint surfaces as indicated by visible openings along bedding surfaces at their tops. During our observation of the slope above the trail from different positions on the trail, we could see 10 to 15 rock masses that appeared to be marginally stable, and we suspect that many others might be found with a more systematic search.

It is our opinion that operating tours of Betatakin Ruins from the Aspen Forest Trail would put the public in a moderate to high risk from rock falls even if the time spent on the hazardous section of trail were kept to brief periods. A long-term operation of tours in this manner would include a high probability that a visitor would eventually be struck by falling rock within the section of trail between points 1-48. If the trail were to be used again, the stability of the rock cliffs near the trail as well as those considerably above the trail would have to be increased. The report by Lachel Hansen & Associates (1985) describes three alternative plans to decrease the hazard to the public, namely by rock-bolting of cliff sections near the trail, boring a tunnel into the cliff behind the trail, or excavating an elevator shaft with an exit tunnel at the canyon bottom.

With any of the above alternatives, the exposure of construction workers to rock-fall hazard would likely be fairly high, especially in the instance of drilling the rock above the canyon trail for bolting. Although precautions would surely be taken for maximum worker safety, complete protection from a large rock falling from high above the trail would be difficult to attain. Because of the persistent rock-fall hazard from the cliffs above the Aspen Forest Trail and the high impact any of the three remediation measures would have on the rock slopes above and below the existing trail, we suggest the idea of constructing a catwalk on the opposite northern canyon wall where the rock cliff is much more massive and relatively free of rock fall.

Covered Catwalk

From discussions with Irv Francisco, John Laughter, and Rick Best of the National Park Service at Navajo National Monument concerning the spectrum of options that have been proposed as solutions to the rock-fall problem, it seems that the placement of a covered catwalk on the northern side of Betatakin Canyon is conceptually attractive because it avoids bedrock that is high in susceptibility to rock fall. The Navajo Sandstone there has approximately the same joint system as that on the south side of the canyon, however, the steep north-dipping joints that present most of the stability problem on the south side of the canyon do not present a significant problem on the north side of the canyon because they dip into the slope instead of out of it. Hence, these joints remain tight and do not contribute to rock fall on this slope.

In addition, a catwalk would only require drill holes in which rods would be anchored to support the catwalk. No excavation of the rock would be required that might remove support from parts of the cliff. The covering of the catwalk would also tend to reduce the fear of heights that many visitors might encounter on an uncovered catwalk. Furthermore, the exterior of the catwalk could be coated with material that would blend well with the color and texture of the natural sandstone.

Admittedly, the above suggestion is only a preliminary concept. A feasibility study would have to be undertaken by experts who are familiar with all of the details that would attend such a construction effort.

Summary and Recommendations

Examination of rock cliffs along the section of the Aspen Forest Trail near the head of Betatakin Canyon in Navajo National Monument indicates a relatively high susceptibility to future rock-fall failure. Joints, fractures, and bedding surfaces in the section where rock falls occurred in 1982 (between stations 35-40) reveal "rock-mass-quality" or Q-values that indicate high susceptibility for rock-fall failure. Similarly, above this section at stations 22 and 23 rock with high susceptibility to rock fall is also encountered. Stereonet analyses of fractures, joints, and bedding show a prevalent set of north-dipping joints that dip at about 65° out of the slope also indicating a high susceptibility to planar sliding failure. These results, together with the observations of frequent small rock falls during the study, suggest that the trail poses a relatively high hazard from rock fall and that the public would be exposed to significant risk if allowed to use the trail in its present condition. Therefore, we advise continued closure of the trail until remedial measures can be implemented.

In view of the overall high to moderate rock-fall susceptibility of the north-facing slope of the Aspen Forest Trail near its head, we recommend that the south-facing canyon wall be considered as an area where a covered catwalk might be constructed with anchors emplaced in drill holes. Such a strategy would avoid the blasting and rock excavation that eventually led to the rock falls in 1982 where rock-slope support had been undermined. It would also avoid the massive excavation that other alternatives such as a tunnel or an elevator shaft would require. If a covered catwalk does not prove to be feasible from the standpoint of safety, cost, aesthetics, or other considerations, then the existing route into Betatakin Ruins from the Tsegi Point Trail remains the logical alternative.

References

Barton, N., Lien, R., and Lunde, J., 1974, Engineering classification of rock masses for the design of tunnel support: Norwegian Geotechnical Institute, Oslo, Norway, 49 p.

Harp, E. L., and Noble, M. A., 1993, An engineering classification to evaluate seismic rock-fall susceptibility and its application to the Wasatch Front: *Association of Engineering Geologists Bulletin,* V. XXX, no. 3, 293-319.

Lachel Hansen & Associates, 1985, Betatakin Trail Technical Study Purchase Order No. PX20004D100, unpublished report to National Park Service, various pagination.

Markland, J.T.,1972, A useful technique for estimating the stability of rock slopes when the rigid wedge slide type of failure is expected: Imperial College *Rock Mechanics Research Reprints*, n. 19.

Osterwald, Frank W., 1982, Letter to Mr. Charles B. Voll, Acting General Superintendent, Navajo Lands Group, National Park Service, 2 p. with 4 B/W accompanying photos from Steven Miller.

Stutzman, Suzanne, 2000, Navajo National Monument, General Management Plan, History of Access, National Park Service, written commun., 5/18/2000, 11 p.

Watts, C.F., 1997, ROCKPACK II, <u>ROCK</u> slope stability computerized <u>PACK</u>, User's Manual, Radford University, Radford, Virginia 79 p.