CONDITION ASSESSMENT REPORT
SPRUCE TREE HOUSE ALCOVE
SANDSTONE ARCH
MESA VERDE NATIONAL PARK
MESA VERDE, CO

James A. Mason, Ph.D., P.E.
Structural, Geotechnical, and Preservation Engineer
Vanishing Treasures Program
National Park Service
Mesa Verde National Park, Colorado
January 19, 2016

Acknowledgements

The process of making this condition assessment of the Spruce Tree House alcove arch required the teamwork of numerous people. First, the Mesa Verde stabilization crew: Tim Hovezak, Kay Barnett, Gay Ives, Neill Smith, and Gary Etheridge; the NPS climbing team: Derek Beitner, David Mealey, Jeff Morris, and Nathan Worsham; also, Scott Travis, Chief of Research and Resource Management, Chapin Research Center; George San Miguel Supervisor, Natural Resource Manager; and lastly, Deputy Superintendent Bill Nelligan and Superintendent Cliff Spencer. All contributed to the effort and discussion.

Abstract

The Spruce Tree House alcove complex is one of the most important and visited sites within Mesa Verde National Park. It is an Ancestral Puebloan habitation compound, built over 700 years ago, that was constructed into the naturally occurring sandstone alcove. Recent rock falls prompted officials to close the site to public access so that the overall structure could be analyzed for stability and safety. Recent visual observations, physical soundings and close surveillances of the arch and alcove rock material, preliminary calculations and re-analyses of prior NPS arch stabilization work has lead the author to question the basic stability and present condition of the arch feature. Based on engineering judgment and proposed detailed engineering analyses to be performed, it is likely that new rock arch stabilization intervention will be required to provide local and global stabilization to restrain future large rock falls and eventually to allow safe access to both park staff and visitors.

This document presents an overview of the issues leading to the site closure decision. From a brief overview of the geologic history and past NPS interaction with the site, to a proposed plan of action, this document guides the reader through issues addressed by professional staff to arrive at the current proposed procedures.

Contents

1. Geomorphological History and Background of the Mesa Verde Region

Mesa Verde National Park is located at the highest elevations of the Mesa Verde cuesta (tilted mesa) in Southwestern Colorado. The observable geology of the Mesa Verde cuesta is dominated by four major formations: 1) Mancos Shale, 2) Point Lookout Sandstone, 3) Menfee Shale, and 4) Cliff House Sandstone (Carrara, 2012) (Griffitts, 1990) from lower elevation (Mancos Shale) to upper elevation (Cliff House Sandstone). Griffitts describes these formations as: "1) Marine, mostly transgressive, offshore, 2) Marine, mostly transgressive, offshore, 3) Continental, stream and swamp, and 4) Marine, transgressive, near shore," respectively. As described by Griffitts, these formations were the result of an inland ocean (Western Interior Seaway), see Figure 1, within the North American Continent that extended from the north of Canada, through the central US and into Mexico, extended east through the Carolinas and bent back to the northeast. The young age and relatively thin overburden pressure resulted in lightly cemented sandstone for the MV region. Evidence of the shallow ocean action can be seen in many areas of the park.

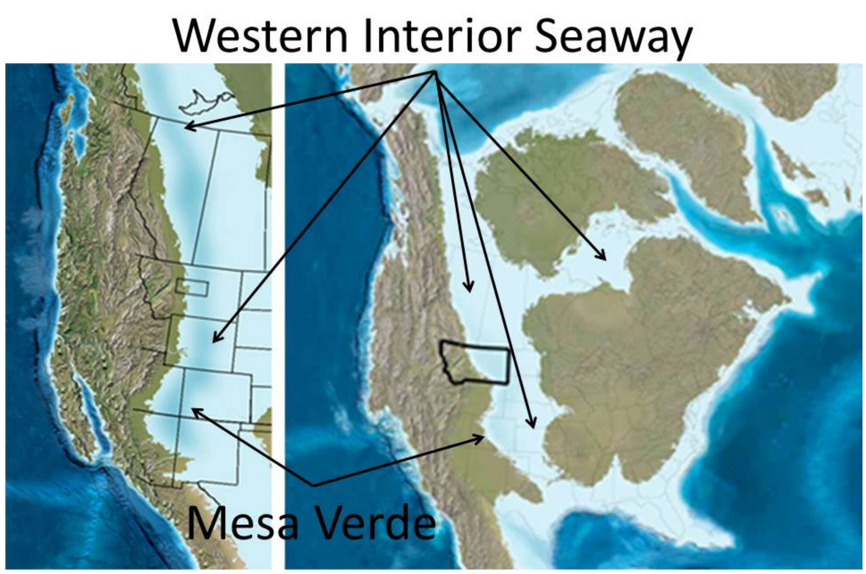

Figure 1. Western Interior Seaway. 90 to 70 million years ago.
http://www.macalester.edu/geology/People/ray/RayGuide/PartI.html
http://www2.nau.edu/rcb7/globaltext2.html

The top surface of the cuesta gently slopes towards the south and is divided by a series of canyons that run in a general north-to-south direction formed by erosional processes. Naturally formed alcoves in the steep walled canyons, mainly in the Cliff House Sandstone formation, provided protection from the environment for later generations of the ancestral Puebloan peoples. It is one of these alcoves that is the subject of this paper.

2. NPS Interaction Chronology with the Spruce Tree House Sandstone Arch

The sandstone arch above the Spruce Tree House (STH) alcove is a naturally occurring structure, approximately 270 feet long. See Figure 2. There are many similar arch formations in other alcoves in the Mesa Verde cuesta. In this case, naturally occurring joint sets (cracks) provided the release and disconnection of the main arch body from the alcove roof structure. For basic stability of any arch structure, thrust reactions at the ends (abutments) must develop, i.e., the arch necessarily has to settle and deflect along the span and push out at the ends. This downward deflection was noted in the early 1900's at STH. Also noted was a continuous crack (rock joint system) running the length of the arch approximately parallel to the outer edge. At some locations, the crack is tight, i.e., the arch is directly against the main roof structure. In a long portion of the arch, the crack has increased in width, up to several feet wide in certain central locations. Concern about the short-term performance of the arch prompted NPS officials in the early 1960's to install rock bolts in the southern portion and seal the crack with concrete. Recent visual observations, and preliminary engineering calculations and modeling (Mason, Oct. 2015), prompted Mesa Verde National Park (MEVE) officials to temporarily close the site to park visitors and staff (Spencer, 2015). This section briefly describes the National Park Service (NPS) interaction with the Spruce Tree House alcove and is based on an internal report by Kay Barnett (Barnett, 2015).

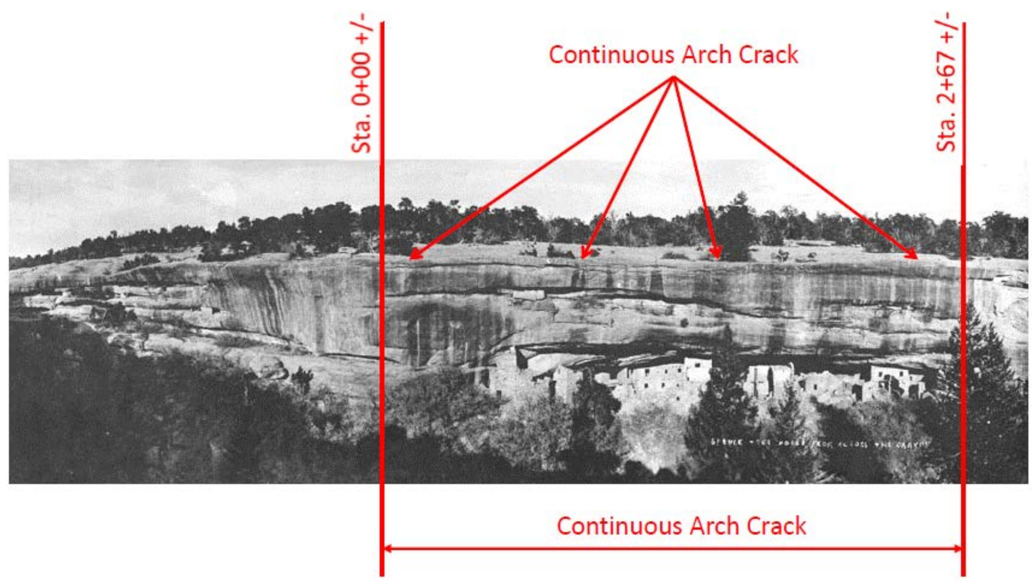

Figure 2. Spruce Tree House from Across the Canyon.
(J. Richardson. 1908. S:/ASCP/08 John Richardson Collection)

Water issues within the STH archeological site and associated alcove were originally documented in 1908 by Fewkes (NPS, 1908). Ground surface water run-off at the top of the mesa followed the natural slope and ultimately flowed through the arch crack and sheeted over the alcove roof edge and onto the ancient dwellings. In an effort to deflect the water, Fewkes "blasted" a trench into the rock back from the outer edge to create a channel that would capture and deflect water away from the alcove. See Figure 3. The trench was minimally effective. The effect of the blasting on the alcove arch was not documented, but in the opinion of this author, could have had detrimental effect on the performance of the arch.

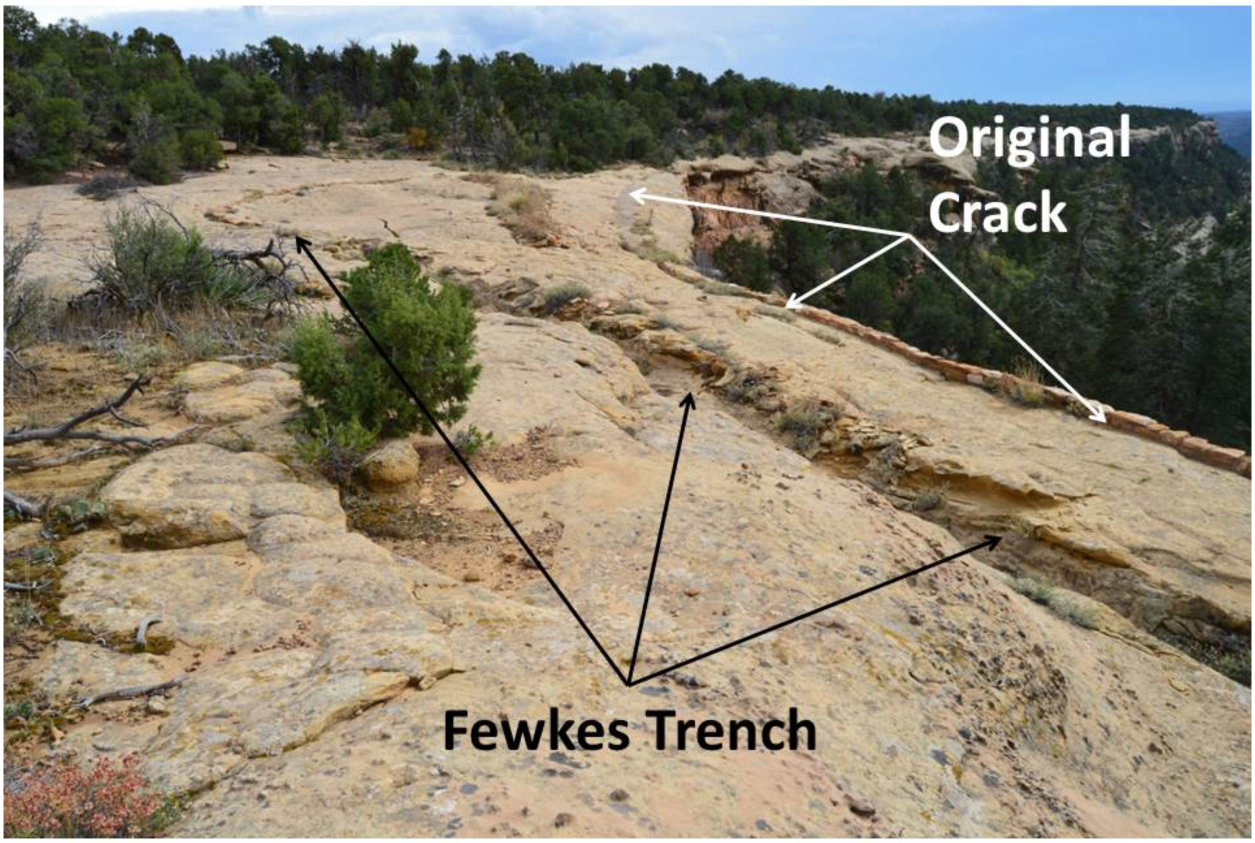

Figure 3. Trench built by Fewkes (1908).
(photo: Mason 2015)

In 1920, there was a large rock fall at the southern end of the alcove mentioned in a later report (Barnett, 2015). Damage from the rock fall was not documented.

The condition of the arch in 1940 brought great concern to NPS officials and is shown in the next three figures. Figure 4 (Lancaster, Neg. No. 0828, 1940, (Richardson, 1940)) shows the view of the crack from the north and looking south. The drainage ditch / scupper is at the bottom of the photo (Sta. 0+10 +/-). The slippage and downward movement of the arch is clearly visible in the photo. Figure 5 (Lancaster, Neg. No. ? (negative missing from files), 1940, (Richardson, 1940)) shows the opening of the crack which allowed a direct path for surface water runoff from the upper surface into the alcove. Also discussed with this photo was ice accumulation with associated ice jacking. Figure 6 (Lancaster, Neg. No. ? (negative missing from files), 1940, (Richardson, 1940)) shows the crack in the process of being cleaned. The back slope of the crack could have been caused by the ice jacking forces and subsequent shearing of the arch sandstone, which indirectly indicates the relatively weak strength of this sandstone.

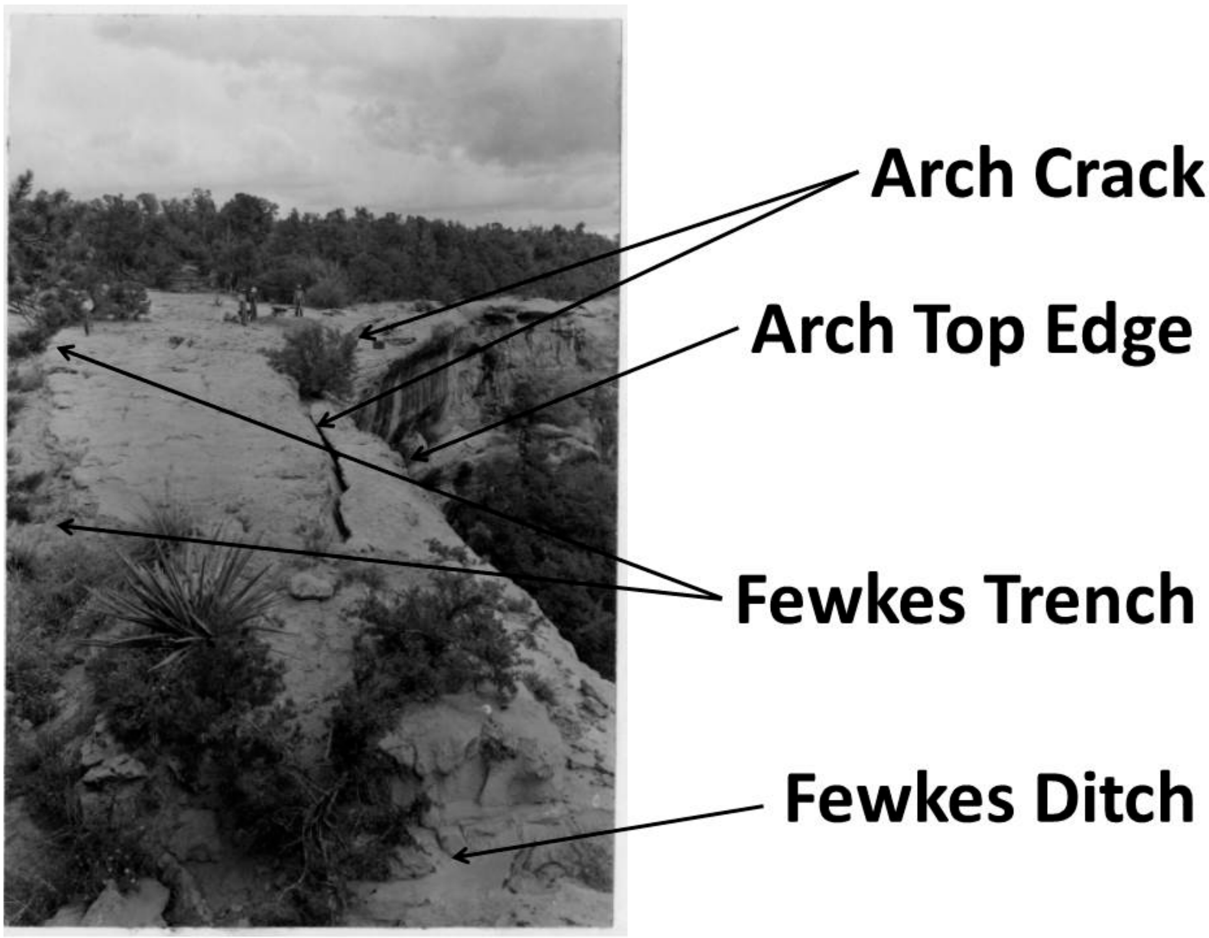

Figure 4. Overall view of crack in Spruce Tree House alcove arch. Looking south. Ditch at left and bottom of photo in near Sta. 0+10 +/-.
(Lancaster, Neg. No. 0828, 1940, Richardson Report, 1940). Labels by Mason (2016).

Two important events happened in 1940: 1) Mr. William Richardson, Assistant Engineer NPS, accurately measured and plotted the outer edge of the arch along the length of the crack (DOI/NPS drawing NP-MV 5315) and assigned survey stationing, and 2) the arch crack was cleaned (as mentioned above), by Lancaster, of debris and plants and subsequently filled at the ends with emulsified asphalt and a roof structure was built over the wider center sections. Lancaster cleaned the crack along the full length and installed a “water-proofing” system to prevent surface water from seeping into the alcove. It appears that the technique was ineffective because of numerous attempts at resealing.

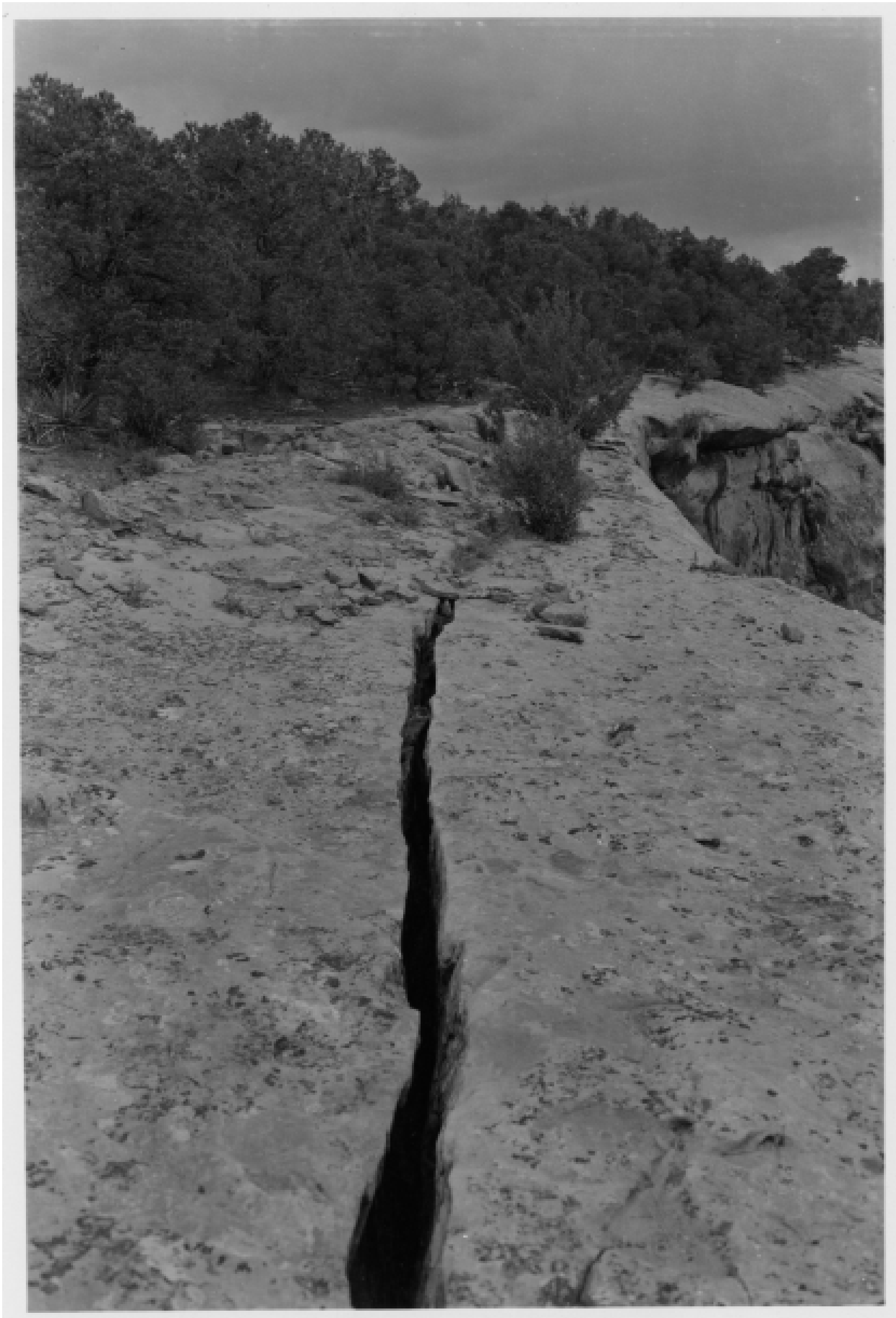

Figure 5. View of crack at southern end. Looking south. Near Sta. 2+30 +/-. (Lancaster, Neg. No. ? (Negative missing from files, Richardson Report, 1940)

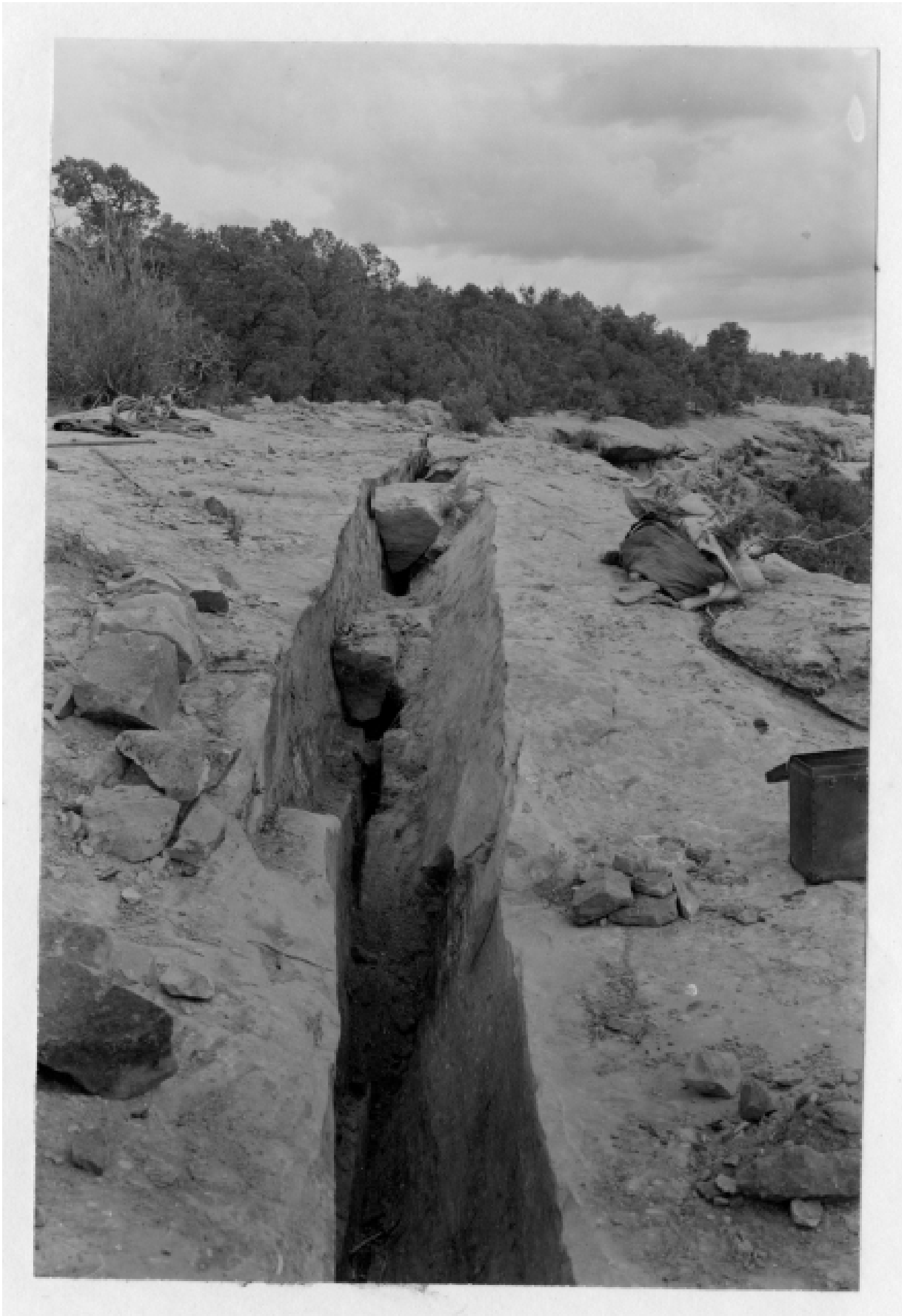

Figure 6. View of widest portion of crack. Looking south. Near Sta. 2+00 +/-. (Lancaster, Neg. No. ? (Negative missing from files, Richardson Report, 1940)

In 1960, there was a rock fall directly south of the 1920 rock fall, near Sta. 2+12. It was at this time that the concern for potential rock falls onto the visitor walkway instigated the discussion of using rock bolts to "hold" the long stone arch in place. In 1962, a contract was awarded to install a total of 46 rock bolts; 39 in horizontal alignment and 7 placed vertically (6 roof bolts and 1 drilled down on top of the alcove near Sta. 2+67). No engineering calculations for this work are on-record, but calculations were referenced in a letter from the Chief Architect Jerry Riddell to the MEVE Superintendent (Riddell, 1962). The rock bolts were described as "1-1/2 inch rods were of the wedge-type and were installed in 3-inch diameter holes, length from 10 feet to 16 feet and the majority was 16-foot lengths" (Unknown, 1963). The steel grade (tensile strength) was not documented. The crack was again cleaned. A system of rolled burlap cloth was pulled by rope up into the lower crack exposure along the complete length creating a plug for the wet concrete that was subsequently cast in the crack. After the placement of the plug, grout injection pipes were located in the crack at regular intervals along the complete length. Crushed stone aggregate was shoveled from the top and filled level with the top surface. Lastly, grout was pumped into the injection pipes and the crack was filled from the bottom up with the pipes being removed after grouting. After the "concrete mixture" had set, it was reported that the rock bolts were tensioned to about 38,000 pounds force which applied a clamping force to the arch, squeezing the arch against the concrete plug and arch roof which pulled against the main body of sandstone alcove. The rock bolts (anchors) were installed between Sta. 1+00 to Sta. 2+67. There was no regular pattern. The rock bolts used were the "swedge" type, an early anchor type, used by the mining industry. The intended application for this anchor type was for hard rock applications where the radial outward pressure of the swedge induces a clamping force exerted by the rock mass onto the anchor (equal and opposite forces). The anchor is then tensioned against the swedge by torqueing the threaded rod against the end bearing plate at the outer rock surface. The bearing plates were recessed into the rock. Grout was injected into the drill hole via a long flexible tube and allowed to set. Lastly, the plates were covered with colored concrete at the end of the operation.

The problem with the swedge device in soft sandstone, such as at the STH alcove, is that the radial outward pressure of the swedge breaks the cementitious bond between sand grains in the immediate vicinity of the swedge. This problem has been documented by other engineers (Wyllie, 1992). Thus, the effectiveness of the clamping force that was applied in 1962 is questionable now, leaving the grout-to-sandstone bond as the resisting mechanism to anchor pull-out. Interestingly, the rock bolt system at STH was designed by A.C. Hawkins who also designed the rock bolt systems at Glen Canyon Dam (Letter from Regional Director T.J. Allen to Chief, Western Office, Division of Design and Construction. June 01, 1961). Glen Canyon Dam has also been experiencing problems with rock spalls in the last 30 years. This issue will be discussed further in Section 5. Figure 7 shows the general region where the rock bolts were installed.

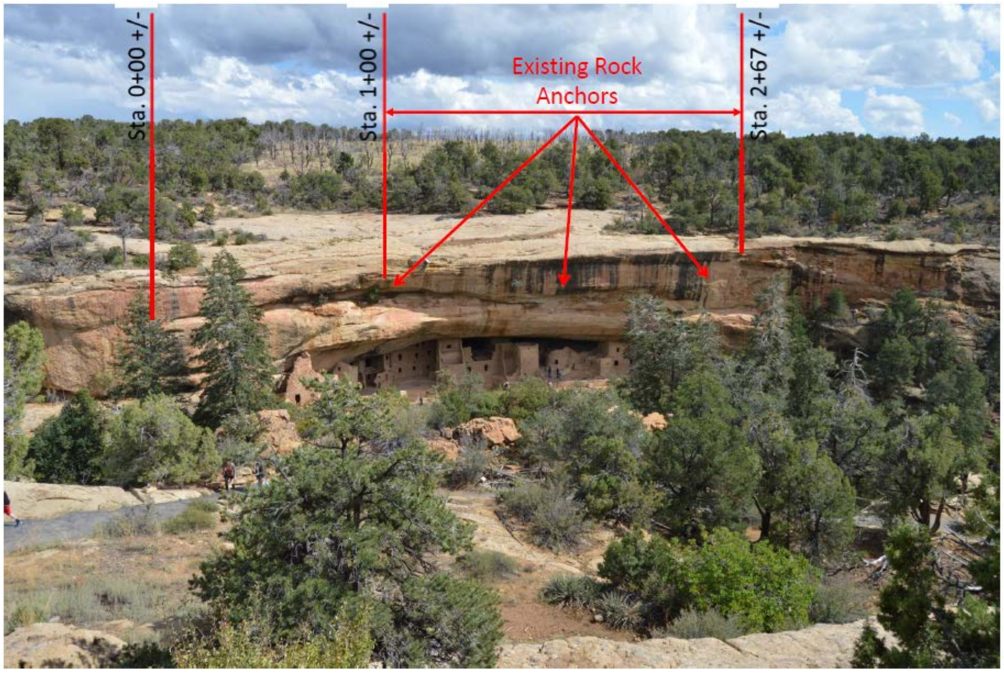

Figure 7. Spruce Tree House. Rock Anchor (Bolt) General Location.
(photo: Mason 2015)

Figure 8 is a working drawing (1962) created to show the as-built locations of the rock anchors in the southern end of the STH alcove sandstone arch. The stationing shown at the top of the figure is correlated with the work by Richardson (1940). These anchor locations were confirmed by the author with high definition photography. It should be noted that the sliver of rock from Sta. 1+42 to 1+72, as shown in Figures 9 and 10, is under the line of rock anchors.

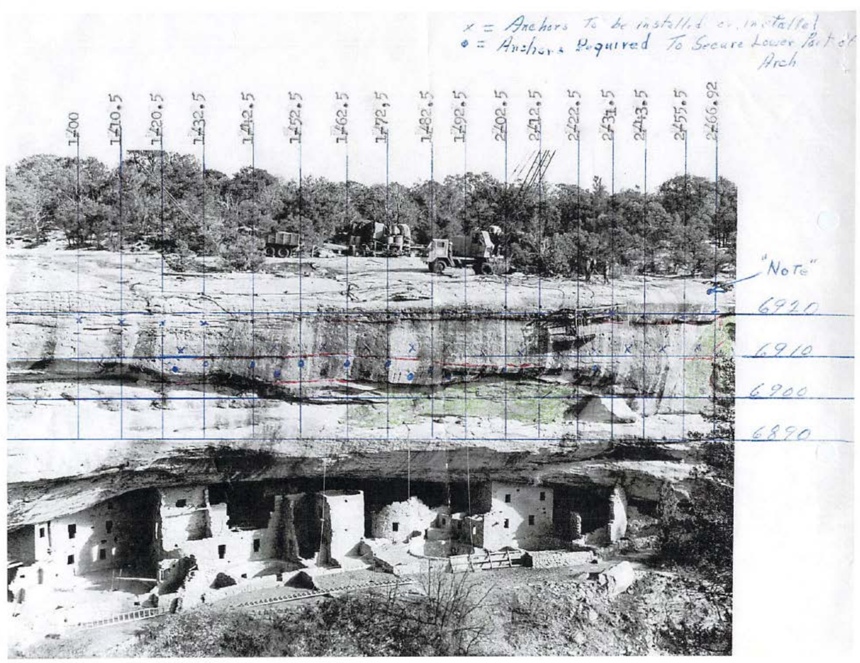

Figure 8. Rock Bolts Installed at Spruce Tree House. (NPS. 1962)

3. Current Field Observations

Visual and photographic observations were made of the STH alcove in early October 2015. The intent of these observations was two-fold: 1) to look at the basic structure for obvious cracks and stability issues, and 2) to identify potential loose material that could fall on people along the visitor path directly below the alcove arch.

Figure 9 shows a portion of the STH alcove arch from about Sta. 1+00 to 2+10. Prior rock fall and potential rock fall are shown in this photo. It must be noted that the installed rock bolts were aligned horizontally directly above the region of prior and potential rock fall structures. Thus, the potential rock fall structure (sliver) has no added restraining components, i.e. rock bolts, leaving only natural mechanics for resistance.

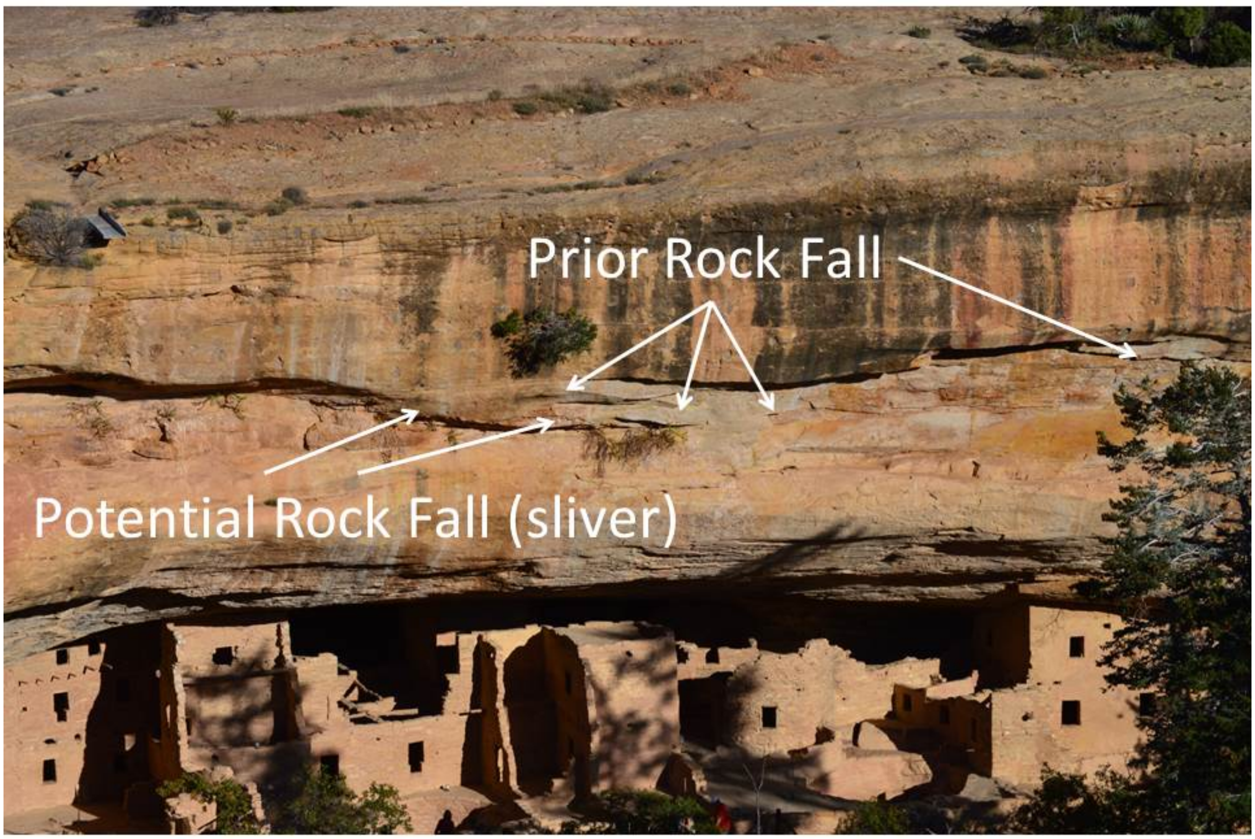

Figure 9. Site Investigation of STH Alcove Structure for Potential Rock Fall.
View from across canyon. (photo: Mason, 2015)

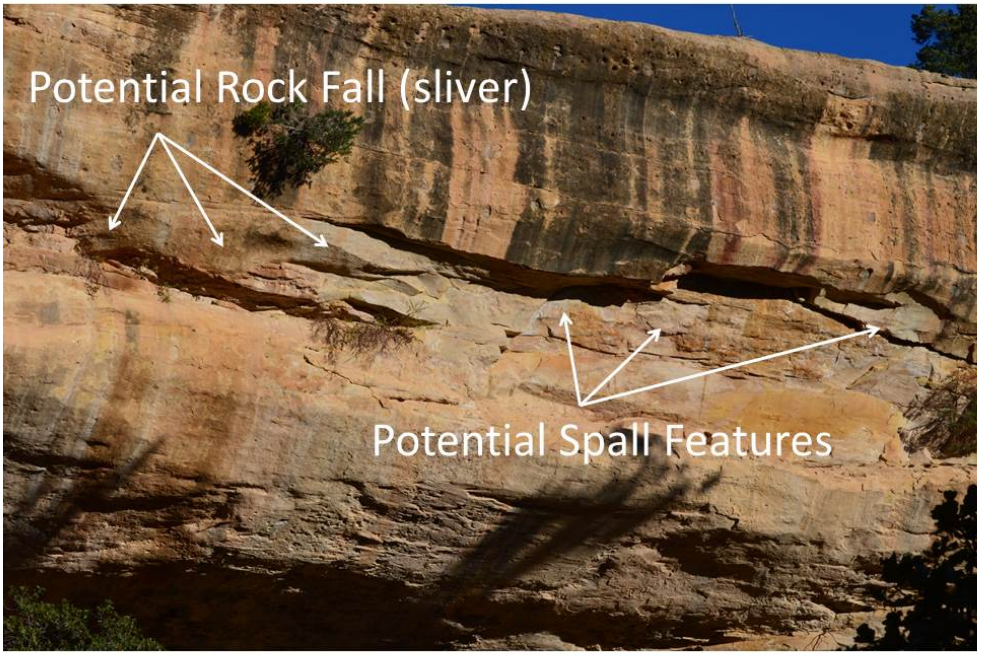

Figure 10. Site Investigation of STH Alcove Structure for Potential Rock Fall.
View from below alcove arch. (photo: Mason, 2015)

Figure 10 shows the same potential rock fall feature (sliver) from the visitor path prior to closure of this area. Also shown in this photo are other smaller potential rock fall features.

Numerous photos and field documentation were utilized to develop a plan of action for the NPS climbing team that came to MEVE to assist with the scaling operation.

In addition to the arch formation and subsequent spalling of the underslung components of the arch, water infiltration into the sandstone has promoted the leaching of the binders from the sandstone. This leads to weakened sandstone or "weathered rock" which ultimately degrades to sand. This is further discussed in Section 5. During the recent inspection and scaling efforts by the NPS climbers, sand was found at numerous locations along the bottom crack edge of the arch. The extent of leaching and degradation is unknown.

4. Recent Scaling Operations

A scaling operation was conducted in early November 2015 by the NPS Climbing Team. See Figure 11. These professional climbers took two days establishing anchorage under the top edge of the alcove roof. The alcove roof top edge extends approximately 15 feet past the alcove lower edge. The majority of the suspect spall material was in-between the upper and lower edges. Thus, they had to install rock climber bolts under the top edge as restraint points to safely hang off the rock face while cleaning loose material. Numerous rappel drops were made to install these devices because of the extremely limited access. Once the bolts and carabiners were installed, the climbers could progress across the rock ledges and methodically and safely remove the loose spall material, which had presented a hazard to people below. Still it was acknowledged that another scaling session is required to remove more material.

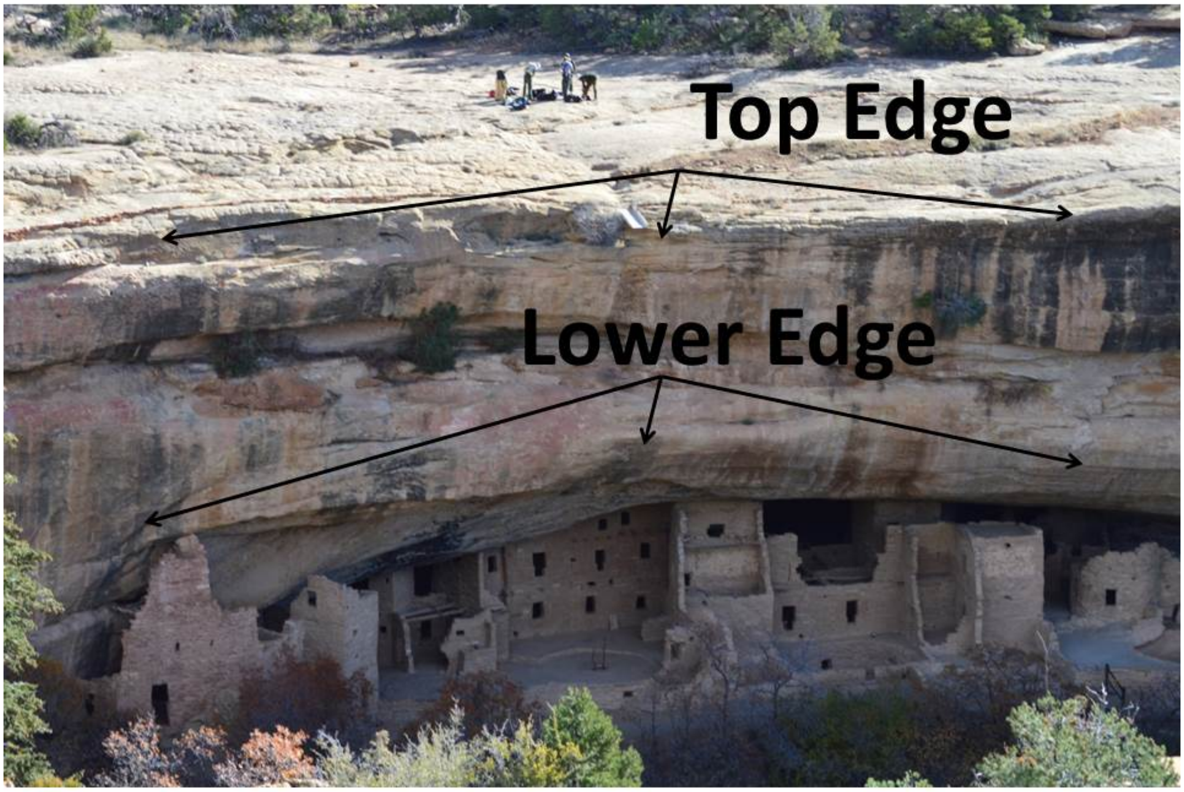

Figure 11. NPS Climbing Team preparing for initial placement of climbing anchors.
(photo: Mason, 2015)

Basic objectives for the scaling operation were:

- Confirm the location of rock anchors.
- Determine the local rock spall hazard.
- Investigate the ends of the arch (abutments) for weaknesses.
- Investigate the condition of the rock sliver under the line of anchors for potential fall and/or spalling.
- Investigate rock joint fill material.
- Investigate the condition of the grout/concrete plug.

The confirmation of rock anchor locations was completed in the office with high definition photographs. The rest of the objectives were completed in the field. Potential small rock spall hazards that could be reached by the climbers were removed. The large sliver will require pinning with rock bolts to prevent it from falling. The abutments were photographed and will be included into the proposed detailed numeric analyses. The rock joint material was confirmed to be composed of silt. The grout plug was intact, but loose in several locations.

Figure 12. NPS climber using a rock hammer to dislodge loose material at the outer alcove edge. (photo: Mason, 2015)

Figure 12 shows one of the climbers using a rock hammer to dislodge loose material. This material was detected in the field by first looking for obvious loose material then sounding the rock surface with the hammer. A “hollow” sound was a positive identifier that material was loose. There was one instance when a climber was suspended from a roof structure (ceiling) and a very large piece of hanging rock was dislodged with only the touch of his hand. He was smartly and safely at arm’s reach and out of the way of the large piece. It fell directly onto the visitors’ path. The material that was removed was found to have a harder, desiccated outer surface with a substantially softer interior. This confirms that the weakening of the sandstone is due to water leaching the calcium carbonate matrix that binds the sand particles in the sandstone.

Figure 13 shows the debris which fell onto the path at the southern end of the site during the scaling operation. A similar amount fell over the edge of the path into the brush downslope of the path. It took about 6 wheel barrow loads to clean the visitors’ paths along the complete length. Thus, at least 60 cubic feet (cf) of material was removed from the alcove edge (at 5 cf per wheel barrow load). Every one of these rocks was a major potential hazard to both staff and visitor.

Figure 13. STH alcove spall material at southern end.

5. Preliminary Engineering Calculations and Observations.

The author investigated the basic mechanics of the anchor system above STH. The cross-sections developed by Richardson (1940) were used as the basis for the graphical analyses. The cross-sections were drawn at approximately 10 ft. intervals. Typical curvilinear fracture surfaces were drawn on the cross-sections using the bottom and top crack as the end boundary conditions for the southerly end of the arch and the bottom crack for the northern end. (Ingraffea, 1998), (ASCE, 1994). It was found that in the wider (thickness dimension) sections, there were many locations where the end of the rock bolt extended only several feet beyond the fracture surface. The majority of the rest of the bolts extended about half of their length (roughly 8 ft.) past the fracture surface. These embedment depths of the anchor are minimal at best for achieving their intended purpose. This conclusion of anchor performance to restrain the arch assumes that the bolt is fully bonded behind the fracture surface (either by swedge action or grout-to-sandstone bond), and that the stone is strong enough to resist conical shear pullout failure. The bottom line is that there are many uncertainties about the anchors' performance as assumed by the original designer that weren't verified in the field during original installation.

In many instances, engineering calculations for geotechnical problems can be constructed in a two-dimensional model and subsequently solved. This type of modeling investigates a typical cross-section of a site with the basic assumptions being that the model represents the complete site. That is, the model could be moved to any location at the site and the new location would be very similar to the model in terms of geometry, stratigraphy, and material properties. The reason for using a 2-D type of modeling is two-fold: 1) Relatively easy numeric models and solutions are constructed and solved, i.e., "text-book" solutions, 2) The 2-D models are relatively inexpensive. This is not the case for the STH alcove arch. The reasons for a detailed three-dimensional model follow.

First, the geometry of the arch changes along its complete length, both in cross-section and alignment. The cross-sectional area of the north end is about half as large the cross-sectional area of the southern end sections. The alignment of the arch in plan (top) view bends by approximately 25 degrees. From this view, the arch looks similar to a boomerang. Thus, the physics of the arch changes from in-plane bending (typical arching action) to a combination of 3 actions: 1) in-plane bending, 2) out-of-plane bending, and 3) out-of-plane rotation. This combination of actions is beyond textbook cases and requires detailed analyses to capture the forces at work at this site and provide information for a rational and safe conclusion.

Second, the natural physics of this unique arch mechanism was radically altered by the installation of the rock bolts and the placement of concrete in the crack behind the arch. The installation of rocks bolts was only executed at the southern half of the arch. Assuming that these are effective in embedment depth (tension), bending, and shear, the rock bolts essentially created a shortened arch (north end) pushing against a new abutment (the south end). The next issue to be addressed is the stability of the southern half now hanging from the alcove roof and whether the installed rock bolts actually hold this portion of the arch. Also, the northerly part of the arch now hangs between the original northern abutment zone and the pinned southerly arch. The mechanics of this section needs analysis.

Third, the very composition of the sandstone could be changed due to the change of water drainage caused by the installed concrete plug. Sandstone is inherently a very porous material in which groundwater could move relatively easily in comparison to hard rock or concrete. Before the concrete plug was installed, groundwater that seeped into the alcove roof could freely drain both vertically and horizontally with the crack providing drainage release. This condition was modeled in an advanced computer program: *SLIDE* (RocScience, 2012). The basic model was constructed from the geometry from Sta. 1+62. See Figure 14. These are partial models investigating the crack and the effect of the concrete dam on ground water movement around the crack. The X and Y axes for Figures 14, 15, and 16 are shown to scale in feet. Full models of the complete alcove cross-section were constructed and showed similar results to the partial models. The sandstone was colored light yellow. The unfilled crack was modeled as a material with no strength, and permeability a thousand times greater than the sandstone. The left hand side (LHS) of the model was assigned as a free draining surface. The top surface and right hand side (RHS) were modeled with a total head condition.

Figure 15 shows the hydraulic gradient, water flow path, and phreatic (water) surface. It can be seen that there is no gradient in the crack (free drainage). The water surface is approximately parallel to the top surface, indicating that the crack filled with water. The arch drainage is roughly planar downward. The overall groundwater movement is towards the lower outer edge of the alcove arch and roof surface. This drainage pattern has been noted in the field.

Figure 16 shows the results of groundwater movement and pore pressure in the sandstone for the case of the crack filled with concrete. For this case, the permeability of the concrete in the crack is roughly 10,000 times less than the porous sandstone. The vectors (arrows) show the ground water flow path. Figure 16 shows that the concrete plug acts as a dam within the alcove roof structure, where the flow vectors point downward alongside the plug. The phreatic surface is approximately parallel to the ground surface upslope and dips down alongside the concrete filled crack. The concrete filled crack is acting as a dam and forcing the ground water flow downward. This phenomenon creates a problem of increased groundwater velocity around the plug, a process which could easily increase the leaching of the calcium carbonate binder in the sandstone, thus leaving sand. This was seen during the scaling operations where piles of sand were found at the base crack of the arch at the north-central part of the alcove.

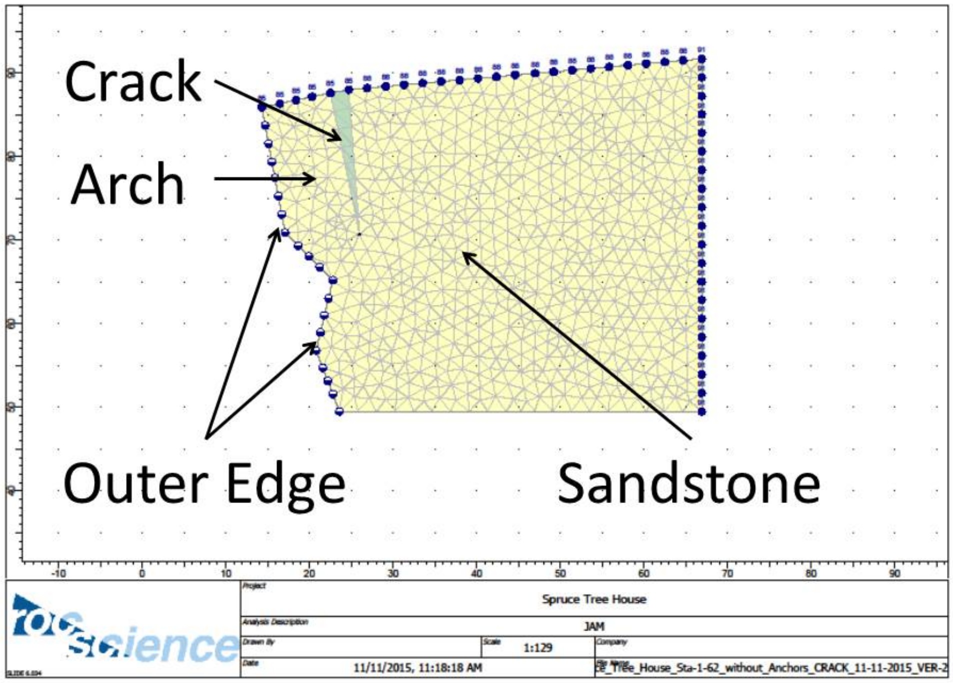

Figure 14. Spruce Tree House alcove. Basic model for cross-section at Sta. 1+62. (Sandstone: Light yellow. Crack: Light green).

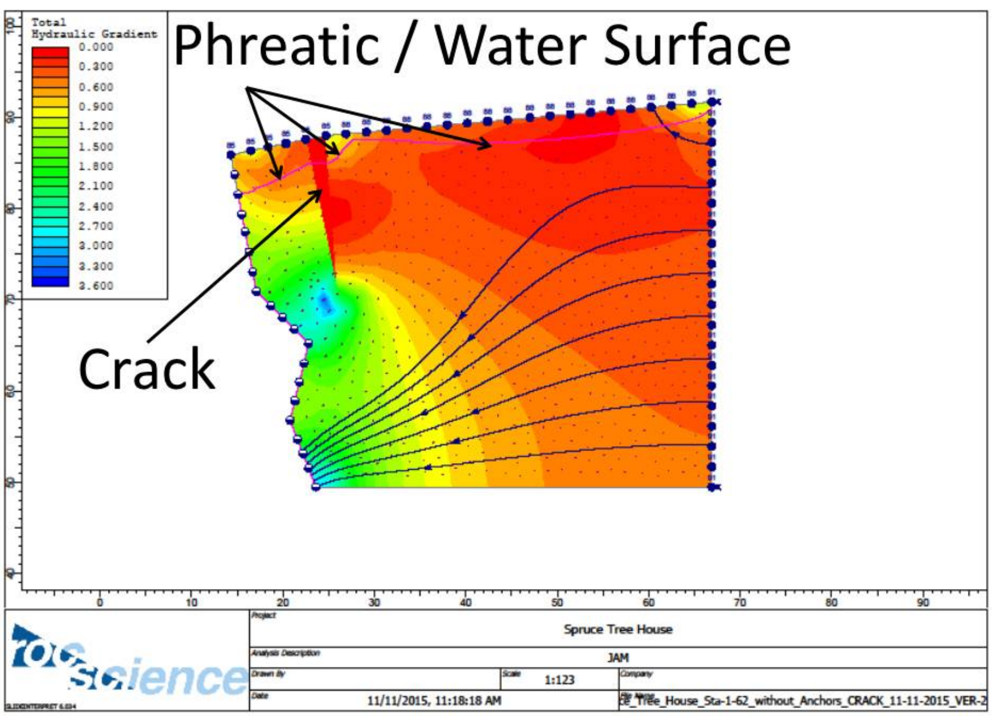

Figure 15. Spruce Tree House alcove. Basic model for groundwater flow at Sta. 1+62. (Crack: Red wedge)

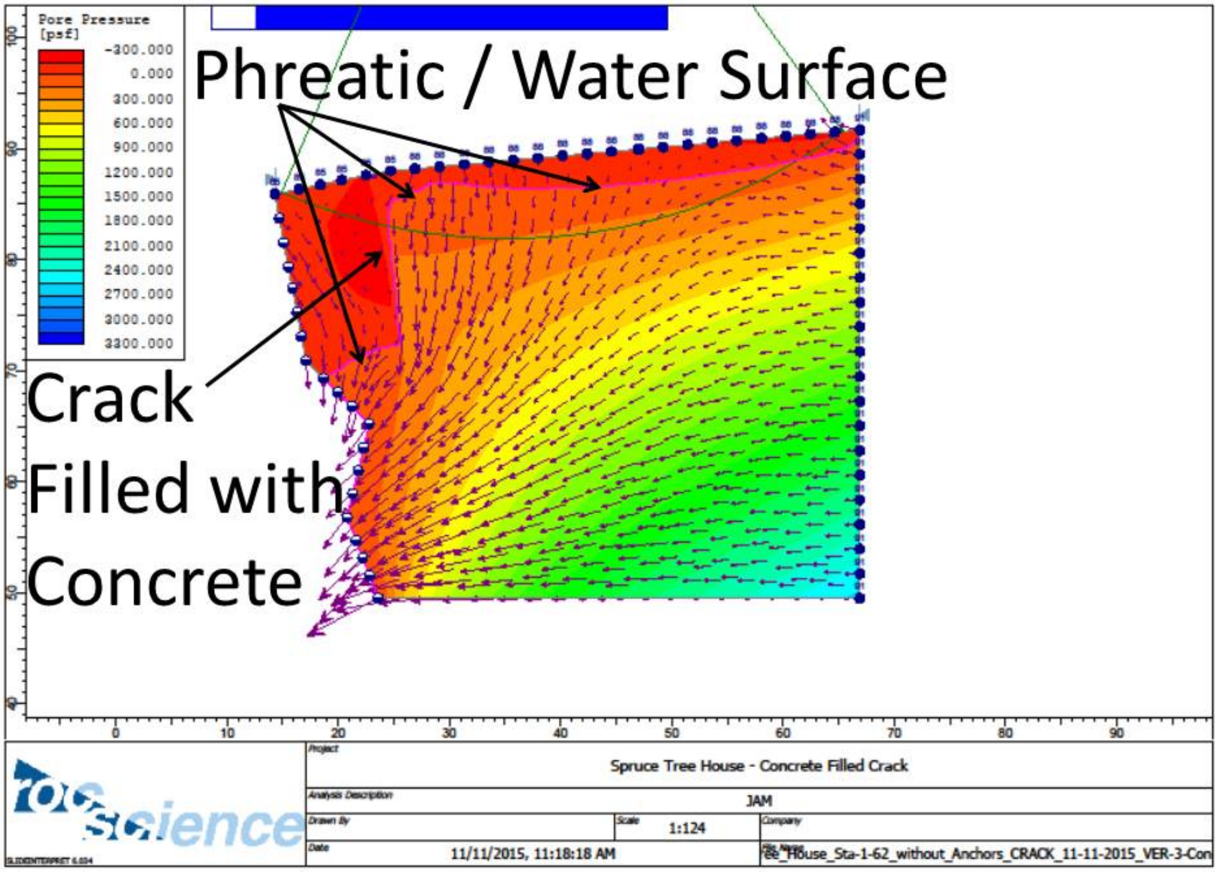

Figure 16. Spruce Tree Alcove. Basic model for pore pressure and groundwater flow at Sta. 1+62. Crack filled with concrete.

6. Proposed Plan of Actions

The proposed plan of action is a four-phased sequential approach: 1) LiDAR scan the complete site including existing structures and on-site geotechnical investigation, 2) Conduct detailed three-dimensional computer-based analyses of the original condition (pre-1900), 1962 strengthening, and probable 2016 strengthening, (a chronological modeling sequence), 3) Develop plans, specifications, and cost estimates to execute probable strengthening, develop bid package, and execute bidding and award of contract, and 4) Execute probable strengthening. Obviously, if the analyses show that additional strengthening is NOT needed then phases 3 and 4 would not be conducted.

The computer modeling of the alcove will be based on LiDAR scans of the complete structure and a geotechnical investigation of the in-situ sandstone and downslope soils. The LiDAR image/point cloud/data set is imported and run through a front-end program *Rhino* (Robert McNeel & Associates, 2015) for surface smoothing and finally uploaded into the main computer analysis program *Flac3D* (Itasca Consulting Group, 2015). The model will begin at the base of the slope continuing all the way around to the top of the alcove roof, including the ancient dwellings, the alcove roof, and arch structure. The lateral extent of the model to the north and south will be roughly 250 ft. at each end. Geotechnical investigations will require very careful core drilling of the sandstone at four locations along the top of the alcove achieved by track-mounted drill rig. These holes will remain sufficiently far from the alcove roof and will be backfilled with a non-shrink grout. Because of the potential of disturbing ancient burial sites at the base of the alcove slope, either non-destructive testing methods (ground penetrating radar) or rational extrapolation methods will be used in these locations. Appropriate laboratory tests will be conducted to assess basic properties and confined shear strength of the sandstone test specimens. The intricacy of the STH complex demands this level of detail.

A major component of the 3-D computer numeric analyses is to establish the current conditions of the sandstone and groundwater to include the material degradation due to natural causes and subsequent loading conditions. In the case of the STH alcove, geo-material degradation is partially due to the change of the groundwater drainage path and velocity, as previously discussed. The second critical features to model are the rock bolts and concrete dam in the original crack to assess the performance of the bolts for arch stabilization. Lastly, proposed stabilization methods are modeled and analyzed.

For the analyses phase, the following list presents objects and deliverables.

Objectives:

1. Develop a global (holistic) understanding of the STH alcove and arch for overall stability. (Limits of analyses: Sta. 0+00 to 2+67, with appropriate lateral and lead edge end conditions (+/- 250 ft.), including downslope to creek.)
    a. Surface topography to be provided (LiDAR Scan).
    b. Model ground water movement.
    c. Estimate original condition pre-1900.
    d. Model the staged construction of 1962 work: Filling of crack and rock anchors.
    e. Estimate global Factor of Safety for both features for both pre and post 1962 work.
2. Develop necessary additional engineering analysis and design for stabilization of either alcove and/or arch.

Deliverables:

1. Report with objectives outcomes discussed.
2. Analyses of ground water and estimated flow location and probable rate.
3. Critical sections stress analysis.
4. Development of strengthening scheme for alcove arch stabilization.
5. Construction consultation.

The development of plans, specifications, and cost estimates to execute probable strengthening are the next sequence of activities. Stringent prequalifications will be demanded of any bidding contractor with exhibited extensive experience for this type of project. Also, very clear guidelines about protection of the natural and cultural resources will be a core component of the specifications. These actions will be performed by Vanishing Treasurers (VT) and MEVE staff. The execution of bidding and award of contract will also be managed by VT and MEVE staff. Lastly, all work will be performed within NPS historic preservation guidelines.

On November 2, 2015, MEVE initiated Section 106 consultation with the State Historic Preservation Office (SHPO) regarding the project. MEVE will be consulting with interested parties and affiliated Native American Tribes as required per 36 CRF 800.

It is estimated that the execution of probable strengthening will require roughly 6 months. This includes mobilization of personnel, equipment and materials, stabilization work, and demobilization from the site.

Bibliography

ASCE, 1994. *Fracture Mechanics Applied to Geotechnical Engineering.* New York (New York): American Society of Civil Engineers.

Barnett, K., 2015. *History of Water Controls, Rock Falls, and the Spruce Tree House Arch. Spruce House Ruin, Mesa Verde,* Mesa Verde: NPS.

Carrara, P., 2012. *Surficial Geology Map of Mesa Verde National Park, Montezuma County, Colorado,* Reston, Virginina: U.S. Geologic Survey.

Griffitts, M. O., 1990. *Guide to the Geology of Mesa Verde National Park.* 1st ed. Mesa Verde Museum Association, Inc.

Ingraffea, A., 1998. *Introduction to Fracture Mechanics. Class Notes. Cornell University.* Ithaca, NY, Cornell University.

Itasca Consulting Group, 2015. *Flac3D,* Minneapolis: s.n.

NPS, 1908. *Reports of the Superintendent of the Mesa Verde National Park and J. Walter Fewkes, in Charge of Excavation and Repair of Ruins to the Secetary of the Interior,* Washington, DC: Government Printing Office.

Richardson, W. H., 1940. *Report of Field Study of Loosened Rock Formations at Spruce Tree House and Square Tower House,* Santa Fe: NPS.

Riddell, J. A., 1962. *Return of Reports. Re: Anchorage of Rock Arch Over Spruce Tree House Ruins,* Mesa Verde: NPS.

Robert McNeel & Associates, 2015. *Rhino,* Seattle: s.n.

RocScience, 2012. *Slide,* s.l.: s.n.

Spencer, C., 2015. *Letter to Colorado State Historic Preservation Officer,* Mesa Verde: NPS.

Unknown, 1963. *Narrative Report. Anchoring of Natural Rock Arch,* Mesa Verde: NPS.

Wyllie, D. C., 1992. *Foundations on Rock.* Vancouver: E&FN SPON.