Rock Slope Remediation at the Penobscot Narrows Bridge

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Abstract

In 2003, Haley & Aldrich, Inc. was retained by Figg Bridge Engineers, Inc. and the Maine Department of Transportation to provide geotechnical services for the replacement of the Waldo-Hancock Bridge and associated approach roadways, which included the design of a concave, semi-circular rock slope that varied in height up to 100 ft along the Prospect approach to the Penobscot Narrows Bridge. During construction of the Prospect approach and excavation of the rock slope, several areas of the rock slope were identified as needing remediation. Between 2005 and 2016, 23 areas along the rock slope were judged to pose potential safety and long-term maintenance issues of varying degree. In 2016, MaineDOT approved and secured funding to remediate nine different areas of the rock slope judged to be "most critical" and "moderately critical." Less critical areas will continue to be monitored and could be remediated during future phases of the project.

Introduction

Beginning in 1931, all traffic heading up U.S. Route 1 (Route 1) along the coast of Maine crossed the historic Waldo-Hancock suspension bridge to access the Down East Maine communities of Bar Harbor, Blue Hill, Castine, and Eastport. The narrow, two-lane, steel bridge spanned the Penobscot River, providing views of the Civil War-era Fort Knox and the town of Bucksport to the north, and Penobscot Bay to the south.

During the spring of 2003, engineers performing an ongoing evaluation of the main-span suspension cables found that the 75-year-old cables were more deteriorated and corroded than originally believed. Subsequently, the bridge was posted and access was denied for vehicles weighing over 24,000 pounds until stabilization and/or remedial repair options for the bridge could be provided. The need to restrict truck traffic had significant economic impact on the local region and destinations in the Down East area of Maine. An immediate decision was made by the Maine Department of Transportation (Maine DOT) to fast-track the replacement of the bridge with a new, modern structure and approach roadways while a stabilization contract was undertaken to strengthen the main-span cables until the new bridge and approaches could be completed.

The location of the replacement bridge (Penobscot Narrows Bridge) is parallel to and immediately downstream of the existing bridge as shown on Figure 1.

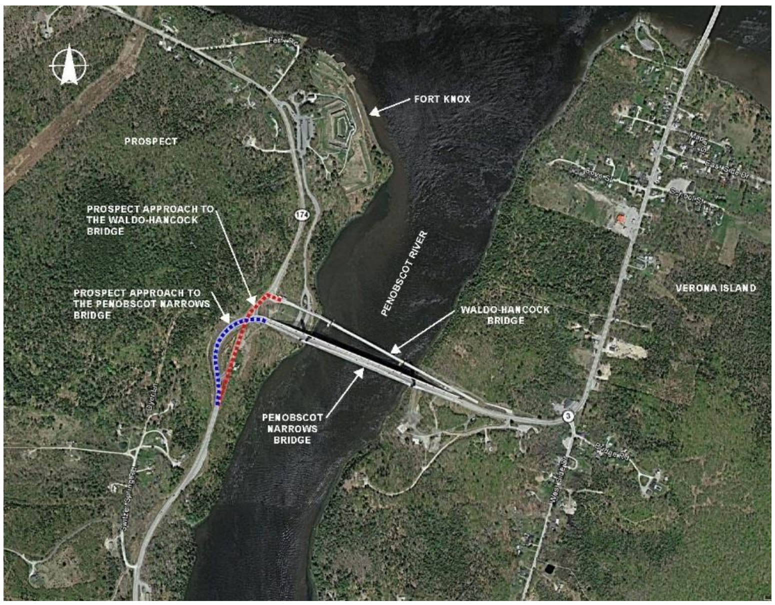

Figure 1 – Project Locus

Prospect approach

Locating the Penobscot Narrows Bridge immediately downstream of the Waldo-Hancock Bridge required realignment of an approximately 775-ft long section of the Prospect approach to the west and into a bedrock-controlled hillside to provide access to the new bridge, as illustrated by the blue dotted line in Figure 1.

The Prospect Approach roadway varies between 40 and 60-ft wide and (shoulder-to-shoulder) and generally consists of two, 14-ft wide travel lanes and two, 8-ft wide outside shoulders. A portion of the roadway has an approximate 14-ft wide curbed median. Ground surface elevations along the concave, semi-circular approach to the new bridge ranged from approximately El. 135 to El. 140 in the vicinity of Route 1 to as high as about El. 250. The proposed grade for the new (i.e., current) roadway ranged from approximately El. 141 to El. 144. As a result, a rock cut up to approximately 100 ft was required to construct the Prospect Approach to the Penobscot Narrows Bridge.

Geologic setting

Based on the Maine Geological Survey surficial geology map of the Bucksport Quadrangle the near surface soil conditions along the proposed roadway consists of thin drift, which is a glacial till deposit that is generally less than 10 feet thick and overlies bedrock.

The Maine Geological Survey bedrock geology map of the area indicates that the bedrock at the site consists of sulfidic schist that contains graded beds (1/32 to 2-in. thick) of quartz-chlorite-muscovite-plagioclase siltstone and pelite of the Penobscot Formation. Andalusite, corderite, and biotite are present in contact metamorphic aureoles adjacent to granitic rocks. Immediately to the west of the site there is a mapped contact between the Penobscot Formation and the Granite of Mount Waldo. The Mount Waldo rock is a light-gray, medium grained, equi-granular biotite granite with no apparent foliation. An excerpt from the Maine Geological Survey bedrock geology map of the area is shown on Figure 2.

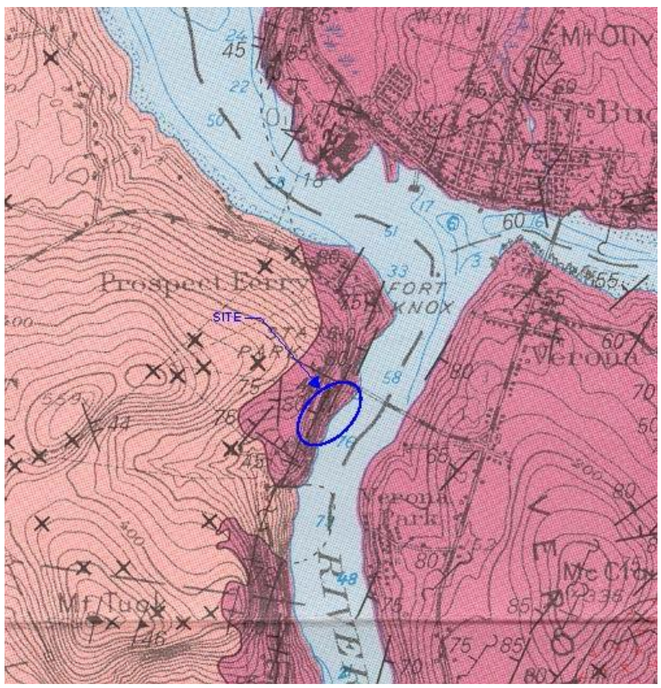

Figure 2 – Bedrock Geology

Original field investigations and conditions

Test Borings and Bedrock Sample Descriptions

Haley & Aldrich completed a design phase subsurface exploration program at the site in September and October 2003. A total of four test borings, designated PRCB1-03 through PRCB4-04, were drilled along the proposed approach roadway as shown on Figure 3.

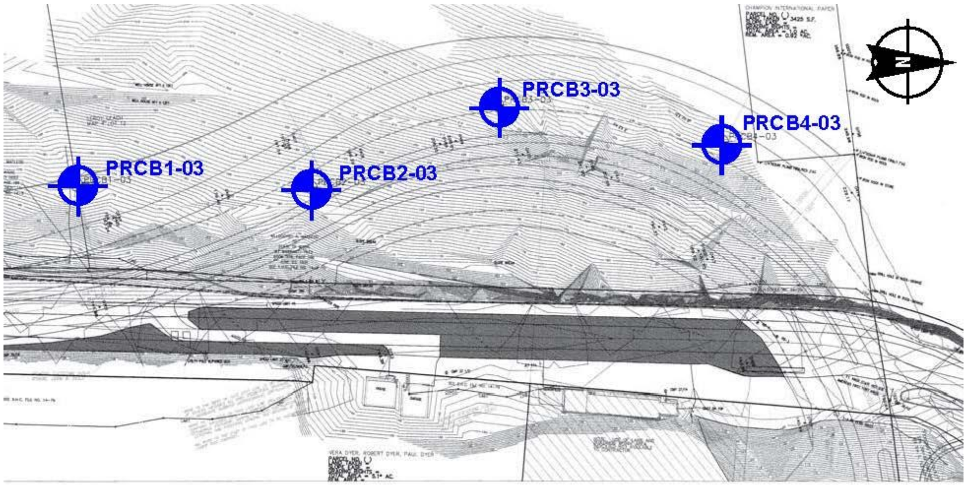

Figure 3 – Test Boring Locations

The test borings were terminated at depths ranging from approximately 28 to 83 ft below the top of bedrock surface.

The bedrock sampled in the test borings generally consist of gray, fine-grained, metamorphic, hard, fresh, metaquartzite. Joints in the rock are typically low angle with steep to vertical foliation joints. The joints are generally tight and discolored, some with heavy oxidation. Veins of gray, medium to coarse grained, igneous intrusive granite were encountered in several of the test borings. Rock quality designation (RQD), a common parameter used to help assess the competency of sampled bedrock ranged from 85 to 100 percent, indicating very good to excellent rock mass quality. Highly fractured bedrock was encountered in localized zones with RQD values as low as 15 percent.

Bedrock Outcrop Observations

In addition to drilling test borings, the geologic conditions at the site were investigated by collecting rock mass data on exposed bedrock outcrops along the existing roadway alignment as shown on Figure 4.

Figure 4 – Existing Rock Slope

A geologic reconnaissance was conducted by a Haley & Aldrich geologist in August 2003. While onsite, Haley & Aldrich collected data on structural geologic properties (e.g., strike, discontinuity dip and dip direction, infilling, visible seepage, persistence, aperture) and general rock mass properties (e.g. weathering/alteration, intact rock compressive strength).

The observed bedrock consists of hard, gray, slightly weathered, fine-grained to aphanitic quartzite with occasional pyrite mineralization and a few calcite veins up to 2-in. thick. The rock mass contains three main joint sets. One set is parallel to foliation and dips steeply to the northwest. Another set dips steeply to the northeast, and the third set is low angle to nearly horizontal. The combined orientation of the joint sets results in a blocky structure. Typical block sizes range from about 2 to 5 feet.

Design rock slope geometry

Based on rock engineering analyses of the data collected and the conditions present along the proposed roadway, Haley & Aldrich recommended that the proposed rock cut be sloped at a nominal 4 vertical to 1 horizontal (4V:1H). Haley & Aldrich also noted the potential for localized geologic features with adverse orientations that may not become apparent until rock slope excavation and that may require stabilization. As a result, Haley & Aldrich recommended that stability assessments be made during construction if fractured or jointed rock was exposed.

Rockfall analyses were completed to determine catchment area geometry at the toe of the rock slope. A catchment area is intended to retain rock blocks that may become detached from the rock slope and would otherwise enter the roadway, creating a hazard.

Haley & Aldrich evaluated the catchment area using the computer program RocFall (Rocscience Inc., 2001). The program simulates falling rocks on the slope to determine percentage of rockfall retained by a catchment area. The program allows for variation of the geometry of the rock slope and catchment area to optimize design. The analyses assumed that the rockfall was generated from a 20-ft tall zone at the top of the rock slope. Rock blocks were assumed to have a mean weight of 1,500 pounds with a standard deviation of 500 pounds, which corresponds to a 2 ft x 2 ft x 2 ft rock block with a volume of 0.3 cubic yards. Considering that the results of the rockfall analyses are highly dependent on irregularities on the rock face that act as launch points for a falling block, launch points were given a 10-degree inclination toward the roadway (based on the observation of a secondary joint set at the site) and four variations to the geometry of the rock slope were analyzed to simulate likely configurations resulting from bench blasting of the slope. An irregular rock face can result from less-than-ideal perimeter control blasting that often occurs in a blocky rock mass.

In addition to the rockfall analysis, a rock slope up to 80-ft high was evaluated using the design criteria presented in the Oregon Department of Transportation (Oregon DOT) Rockfall Catchment Area Design Guide. The design guide relates the height and slope of the rock face with the width of the catchment area (horizontal distance from the toe of the slope to the edge of the pavement) and the backslope of the ditch.

Based on the results of the rockfall analyses and the guidance provided by the Oregon DOT Rockfall Catchment Area Design Guide, Haley & Aldrich recommended a 22-ft wide catchment area including a 14-ft wide unpaved foreslope (4H:1V) and an 8-ft wide paved shoulder. Haley & Aldrich estimated that the recommended catchment area would contain between 80 and 90 percent of rockfall depending on the quality of perimeter control blasting and other factors. Haley & Aldrich also recommended that a clearing limit of 25 feet be established at the top of the rock slope and all soil within 10 feet of the top of the slope be removed and that a rockfill toe buttress be provided to prevent soil from encroaching on the top of the slope. The recommended rock slope geometry and catchment area are shown on Figure 5.

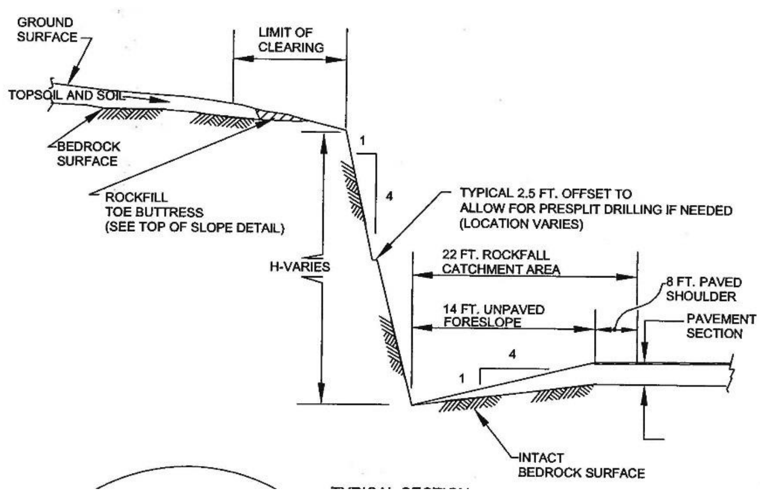

Figure 5 – Design Rock Slope and Catchment Area Geometry

Rock slope construction and inspection

Perimeter control and production blasting and excavation of the rock slope began in late 2004/early 2005 and was substantially complete by June 2005. Construction progress photographs are shown below on Figure 6. The completed rock slope is shown on Figure 7.

Figure 6 – Blasting and Rock Slope Excavation

During construction and excavation of the rock slope multiple site visits were made by Haley & Aldrich staff during which portions (Areas) of the rock slope were identified as needing remediation (stabilization). Draft sketches, details and/or specifications for remedial measures were prepared during construction and again in 2005/2006 in an effort to stabilize the identified Areas. MaineDOT elected not to perform the recommended rock slope remedial work during the original bridge and approach roadway construction due to project-specific constraints at the time of the work.

In 2009 and again in 2012, Haley & Aldrich was re-engaged by MaineDOT to further evaluate the condition of the rock slope, design new and/or refine previous stabilization measures and prepare bid documents in an effort to stabilize identified Areas along the rock slope during demolition of the Waldo-Hancock Bridge. MaineDOT elected to temporarily delay proposed rock slope remedial work until after the completion of the bridge demolition. As a result, the 2012 Haley & Aldrich work plan was modified to include recommendations for a long-term rock slope maintenance and monitoring (M&M) program. The condition of the rock slope was monitored and documented by MaineDOT in 2014.

Figure 7 – Completed Rock Slope

2015 field investigations and rock slope area assessment

July and October 2015 site inspections

In 2015, MaineDOT approved and secured funding to remediate (stabilize) portions of the rock slope judged to be "most critical" and "moderately critical" as it relates to public safety and annual maintenance. As a result, Haley & Aldrich was re-engaged and conducted a site visit with MaineDOT geotechnical engineers in July 2015 in conjunction with MaineDOTs annual M&M inspection. The primary purpose of the site inspection was to:

- Observe and document rock slope conditions in the Areas where remedial measures were previously (i.e., between 2004 and 2012) recommended and compare the previous and current rock slope conditions to assess whether the recommended remediation measures were still appropriate and what additional remedial measures, if any, may be needed;
- Observe and document rock slope conditions in Areas where remedial measures were not previously recommended and compare the previous and current conditions to assess whether remedial measures may be needed;
- Identify Areas where additional inspection (e.g., rope access inspection) would be needed to collect additional structural information to determine the final priority/ratings for more critical Areas; and,
- Assign preliminary ratings to each of the identified Areas, ranging from "least critical" to "most critical" in an effort to further refine work scope to be completed during subsequent phases of the project.

Several Areas of the rock slope were assigned preliminary ratings of "most critical" and "moderately critical" as a result of the July 2015 site inspection and were judged by Haley & Aldrich as needing follow-up investigation so that they could be accessed from the top of the rock slope using rope access techniques, and observations made in Areas and from perspectives that are not visible from the base of the slope. In addition, the supplemental field investigation provided an opportunity to collect sufficient information to determine vegetation/tree removal requirements both on top of the rock slope and on the rock slope face itself. In general, the primary purpose of the site inspection was to:

- Observe rock slope Areas initially ranked "most critical" and "moderately critical" that were previously judged to pose the highest potential risk for rockfall and where remedial measures were previously recommended.
- Observe, measure and document dimensions of specific rock slope Areas, key rock block attributes, discontinuity location/orientation/condition and identify zones of loose rock to support determination of the final priority/ratings and preliminary and final design of remedial measures.
- Determine the final priority/ratings for each Area based on the additional data collected.

A site inspection was completed by a two-person team of Haley & Aldrich engineering geologists in October 2015 that allowed for a detailed examination of several rock slope Areas previously ranked as "most critical" and "moderately critical". Rope access techniques were used, as shown in Figure 8, to descend the rock slope face from the area above the top of the slope.

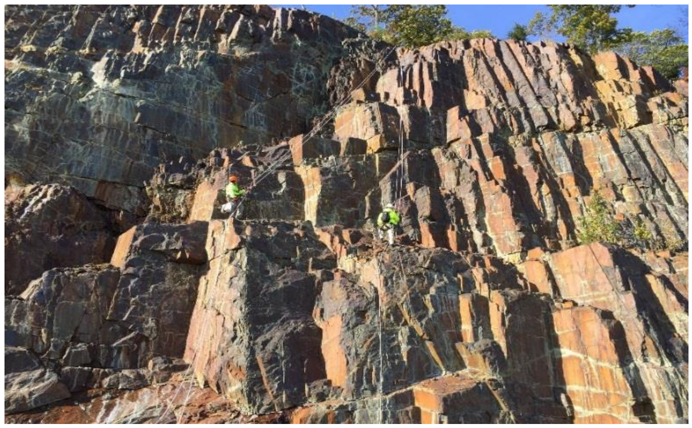

Figure 8 – Site Inspection using Rope Access Techniques

The rope access approach allowed Haley & Aldrich personnel to directly observe rock structure and the spatial relationships between rock blocks that were not visible or discernable by routine observations made from the base (roadway level) or from the top of the rock slope. Observed attributes included near-vertical separation joint orientations controlling potential block release, zones of weakened and sheared rock, sliding plane conditions where controlling joints dip out of the rock slope face towards the roadway, and measurements of rock block and other critical area dimensions. Observation and documentation of the rock slope conditions also included determining the structural geologic properties of the bedrock (e.g., discontinuity dip and dip direction, frequency, infilling, visible seepage, persistence, aperture) and rock mass properties (e.g. weathering/ alteration, estimation of intact rock compressive strength).

Rock slope area assessment

Between 2005 and 2015 Haley & Aldrich identified a total of 23 Areas along the rock slope, designated Area 1 through Area 19 (including 1A, 4A through 4C and 5A), that were judged to pose potential safety and long-term maintenance issues of varying degree. Final relative risk ratings were assigned to each Area after completion of the October 2015 site inspection and are summarized in Figure 9.

Area No.[1]	Approximate Location (Sta.)	Year Identified	Original Stabilization Recommendations	2016 Final Rating[2]	Preliminary Stabilization Recommendations[3]	Remediation in Initial Phase of Work[4]
1	360+50	2005-2009	Type B Rock Dowels		2 Rock Dowels	Yes
1A		2015	NA		NA	No
2	361+50	2005-2009	Type B Rock Dowels, Shotcrete, Shotcrete Rock Drains		NA	No
3	363+00	2005-2009	Type B Rock Dowels, Shotcrete, Shotcrete Rock Drains		NA	No
4A	364+00	2005-2009	Type B Rock Dowels, Rock Drains		2 Rock Dowels	Yes
4B			Type B Rock Dowels		2 Rock Dowels	Yes
4C			Type B Rock Dowels		3 Rock Dowels	No
5	365+00	2005-2009	Type A and B Rock Dowels, Wire Mesh		Anchored Mesh, 32 rock dowels	Yes
5A			Type B Rock Dowels		Check Scaling	Yes
6	365+50	2005-2009	Type B Rock Dowels		Cable Lashing, 4 rock dowels	Yes
7	366+00	2005-2009	Type A Rock Dowels, Shotcrete, Shotcrete Rock Drains		NA	No
8	366+50	2005-2009	Shotcrete, Shotcrete Rock Drains	S N	NA	No
9	366+75	2005-2009	Type B Rock Dowels, Shotcrete, Shotcrete Rock Drains		Scaling, 6 Rock Dowels	Yes
10	359+50 to 360+00	2005-2009	Wire Rope		1 Vertical Rock Dowel	Yes
11	358+75	2005-2009	NA		NA	No
12	358+75	2012	NA		NA	No
13	359+75	2012	NA		NA	No
14	364+50	2012	NA		Check Scaling	Yes
15	364+50	2012	NA		Check Scaling	Yes
16	364+50	2012	NA		2 Vertical Rock Dowels, 4 Sub-Horizontal Rock Dowels	Yes
17	359+75	2015	NA		NA	No
18	362+50	2015	NA		NA	No
19	360+50	2015	NA		NA	No

Legend:

- "MOST CRITICAL"
- "MODERATELY CRITICAL"
- "MARGINALLY CRITICAL"
- "SLIGHTLY CRITICAL"
- "LEAST CRITICAL"

Figure 9 – Final Rock Slope Remediation Area Assessment

Considering that available funding for rock slope remediation was limited, MaineDOT requested that Haley & Aldrich develop rock remediation design recommendations for Areas rated as “Most Critical” and “Moderately Critical”. Less critical Areas (i.e., “Marginally Critical” to “Least Critical” Areas) will continue to be monitored during future M&M inspections and potentially remediated during future phases of the project, if additional funding is secured and made available.

Rock slope remediation design and construction

In general, rock slope remedial measures included the use of passive rock reinforcement elements (i.e. dowels), anchored (“pinned”) wire mesh netting, wire rope cable lashing and rock scaling and vegetation removal. Remediation elements were selected based on technical feasibility, cost and aesthetics.

Haley & Aldrich was responsible for rock remediation design and full-time field engineering and construction oversight that was provided by a combination of experienced engineering geologists and geotechnical engineers during the period 5 October to 22 November 2016. The rock remediation work was completed by Apex Rockfall Mitigation, LLC. (Apex) who was the specialty rock remediation subcontractor to the Lane Construction Corporation (Lane). In general, Apex was responsible for rock slope scaling and vegetation removal, installation of rock dowels, and the installation of anchored wire mesh and cable lashing systems.

Rock slope scaling and vegetation removal

In general, scaling was completed along the entire rock slope, from the top to the bottom, to remove loose rock fragments/blocks, soil and vegetation that posed a falling hazard both during and after construction. All scaling activities were completed at night and while vehicular traffic was stopped during 25-minute (maximum) intervals as shown on Figure 10. All traffic was allowed to clear prior to the next 25-minute stoppage in accordance with project requirements.

The majority of scaling was completed using hand tools consisting of pry-bars, picks and/or shovels. Areas that contained heavily fractured rock and soil were scaled using pressurized air. Large rock blocks were scaled using a combination of hand tools and inflatable air bags.

Figure 10 – Rock Slope Scaling at/near Area 9

Rock Dowels, Wire Mesh Netting and Wire Rope Cable Lashing

A total of 67 rock dowels were installed (61 were included on the contract drawings) within seven different areas of the rock slope, which included six additional rock dowels that were installed in Areas 1, 5 and 10 as summarized below in Table 1. The number and length of rock dowels in each Area were determined based on the size of the rock block, the presence of discontinuities and the minimum required design load.

Table 1 – Rock Dowel Summary

Area	Total Number of Rock Dowels		Notes
	Designed	Constructed	
1	2	3	rock dowel A1-3 (15-ft long) added
4	7	7	
5	32	36	four boundary cable anchors (4-ft long) added in the upper left and right and lower right and left corners of the wire mesh
6	4	4	
9	6	6	
10	2	3	rock dowel A10-3 (5-ft long) added
16	8	8	

All rock dowel locations were marked by Haley & Aldrich prior to drilling. The rock dowel holes were drilled using either a specialty “wagon” drill rig suspended from ropes or a “plugger” drill mounted to a manlift as shown in Figure 11. The 2-½ to 3-½ -in. diameter holes (minimum 2-3/8 in. required) were generally drilled in close proximity to the marked location with the exception of two, which were relocated by Haley & Aldrich after scaling activities were completed. The holes were drilled to the depths specified unless fractures with significant soil infilling were encountered in the holes during drilling, based on contractor-estimated drill action, like variable drilling rates and loss of air pressure.

Figure 11 – Rock Dowel Drilling with Wagon Drill (left) and Manlift (right)

In accordance with project requirements, a minimum of one pull test was completed in each area of the rock slope where rock dowels were installed (12 total). After receipt of acceptable grout compressive strength laboratory test results and hydraulic jack calibration information, Haley & Aldrich selected the rock dowels to be tested either at random or based on drilling or installation conditions, like the presence of soil seams or lower grout strengths. Each rock dowel was loaded incrementally up to 125 percent of the design load (i.e., 84 kips), which was based on the minimum required pullout strength for the rock mass, and displacement/deformation was measured via two dial gauges that were setup on opposite sides of the dowel bar. Total displacement/deformation for each rock dowel tested was less than the maximum allowed.

Upon successful completion of pull testing, rock dowels were outfitted with the appropriate hardware (bearing plate, washers, nuts) as shown in Figure 12. Prior to installation, any voids observed beneath the dowel bearing plate following grouting were backfilled with dry-packed grout. Per specification, the setting force was applied by tightening the nut against the washer and plate to remove loose float from the washers and plate using a torque wrench. The nuts were tightened with a minimum applied torque of 150 ft-lbs.

Figure 12 – Wire Mesh Netting and Wire Rope Cable Lashing in Areas 5 and 5A

Wire mesh consisted of TECCO® G65/3, which has enhanced corrosion protection give the project's proximity to a marine environment, and was powder coated to blend into the natural color of the rock slope.

Conclusions

Beginning in 2005, Maine DOT has effectively managed one of their greatest geotechnical assets in the rock slope along the westerly approach to the Penobscot Narrows Bridge as shown in Figure 13. Through their continued persistent efforts to secure funding and in implementing an annual M&M program MaineDOT has reduced risk, kept the infrastructure in good condition while maximizing the available funding. High risk rock slope scaling was completed at night to reduce the potential for impact to the traveling public and aesthetic features (i.e., color selection of wire mesh netting and cable lashing powder coating) were used to blend the remedial measures seamlessly into the natural surroundings.

Figure 13 – Final Rock Slope Condition

References

1. Wones, David R., 1991, Bedrock geologic map of the Bucksport [15-minute] quadrangle, Waldo, Hancock, and Penobscot Counties, Maine: U. S. Geological Survey, Geologic Quadrangle Map GQ-1692, color map, scale 1:62,500.
2. Pierson, L., Gullixson, F., and Chassie, R., 2001, Rockfall Catchment Area Design Guide, Final Report SPR-3(032), Oregon Department of Transportation – Research Group.