Title: **Condition Assessment And Service Life Estimates For Rock Reinforcement: Case Study**

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Condition Assessment And Service Life Estimates For Rock Reinforcement: Case Study

By Richard Lane and Kenneth Fishman

Abstract. Thirty-year old rock reinforcements at the Barron Mountain rock cut along I-93 near Woodstock, NH are the subject of condition assessment and estimation of remaining service-life. Two types of rock reinforcements are installed at Barron Mountain including: (1) partially bonded, resin grouted, prestressed rock bolts, and (2) fully bonded, Portland cement grouted, passive tendons. Phase I of the condition assessment includes an evaluation of site conditions, a review of installation details, estimation of remaining service life and conducting nondestructive testing. The second phase of the project (Phase II) includes lift-off tests; and physical, chemical and metallurgical testing on steel and grout samples retrieved from exhumed reinforcements. Results from Phase II are used to verify results from NDT obtained in Phase I.

Examination of exhumed samples tended to verify results from NDT that recognized the occurrence of corrosion. Tendon elements protected by Portland cement grout were in very good condition compared to the resin grouted rock bolts and this observation is also consistent with results from NDT. Section loss of approximately 20% of the original cross section near the backside of the anchor plate was observed in three of the rock bolt samples. This is consistent with expectations based on site conditions, installation details, and existing mathematical models of service life. Reasonable agreement was recognized between results from lift-off testing and NDT.

INTRODUCTION

Since the early 1970's, transportation agencies have employed rock reinforcement including rock anchors and rock bolts to stabilize rock cuts and mitigate rock falls. Therefore, some of the earlier installations are approaching service lives of approximately 30 to 40 years. Because visual observation of conditions at the anchorage assembly is often not indicative of potential problems, the condition of existing systems is uncertain. Based on the results of recent research, a recommended practice was developed to evaluate the condition and remaining useful service life of existing metal tensioned systems in geotechnical applications (NCHRP, 2002). The recommended practice employs nondestructive testing (NDT), supplemented with results from invasive testing, to evaluate the elements and perform a condition assessment. This paper describes a case study involving implementation of the recommended practice, demonstrating the utility of the results from condition assessment, and application of these results to develop an action plan to retrofit and extend the expected service life of the system.

Background and History

In 1972, during the construction of Interstate 93 in Woodstock, NH, a rockslide occurred at the base of Barron Mountain. The slide, consisting of approximately 17,000 cy (12,998 m^3) of rock, buried the I-93 northbound barrel. A redesign of the roadway was immediately undertaken to include stabilization of the rock slope by installing extensive rock reinforcement and instrumentation. Rock tendons 50 to 60 ft (15.4 m to 18.3 m) in length were installed at an upward angle to counteract sliding along an anticipated potential failure plane. Shorter, 10 to 30 ft (3.1 to 9.1 m) long, rock bolts were installed to keep the rock mass intact; to preserve the full gravity effect of the rock bench used to maintain global stability, and to prevent minor rock falls onto the highway. The rock reinforcement system has performed well to date and no major rock slides or rock falls have occurred in this area subsequent to construction.

The estimated design life of unprotected rock reinforcement systems is approximately 50 years (Kendorski, 2003). The New Hampshire Department of Transportation (NHDOT) is concerned with the longevity of the system given half the anticipated design life has passed. To address this concern the NHDOT undertook condition assessment and evaluation of the thirty-year old rock reinforcements at Barron Mountain. The condition assessment followed the recommended practice from NCHRP 24-13 (NCHRP, 2002) and was performed in two phases implemented in the summer and fall of 2003 and 2004.

Phase I of the condition assessment included an evaluation of site conditions, a review of installation details, estimation of remaining service life and condition assessment using nondestructive testing. The second phase of the project (Phase II) consists of invasive testing of selected rock bolts and tendons to verify results from Phase I. Invasive testing includes lift-off tests; and physical, chemical and metallurgical testing on steel and grout samples retrieved from exhumed reinforcements. Corrosion of reinforcements is observed in terms of surface distress and metal loss. Data from Phase II are compared to results and interpretations from NDT. The comparison is in terms of qualitative and quantitative condition assessment relative to the reinforcement population at the site, as well as features and attributes observed for specific reinforcements.

Geology of Rock Slope

The rock cut, shown in Figure 1, reaches a maximum height of 130 ft (39.6 m), is 600± ft (182 m) in length and has a 30 ft (9.1 m) wide rock bench at approximately 90 ft (27.4 m) above ditch elevation along the southern portion of the cut. The southern half of the rock cut (right side of Figure 1) is composed of gneiss, which grades into foliated, quartz mica schist in the northern section. A large andesite dyke, exposed along the entire height of the cut, intrudes into the country rock along the contact between the two rock formations. Smaller basalt dykes are visible on the rock face. The rockslide occurred along a highly fractured, mylonite zone, which dips toward the road at approximately 38 degrees (Fowler, 1976a and 1976b). The failure surface from the 1972 rockslide is visible in the lower left corner of the rock slope as shown in Figure 1.

Details of Existing Rock Reinforcement

Figures 2 and 3 portray the rock bolt and tendon installations. Rock bolts and rock tendons include 1 in (25 mm) and 1.25 in (32 mm) diameter steel thread bars, respectively. Most of the reinforcements are Dywidag, Grade 150, high-strength prestressing steel thread bars, but some rock bolts are Grade 80 threaded steel rods. Prestressed rock bolts are end point anchorages, grouted at the distal end with polyester resin grout, and supported by an anchorage assembly

FIGURE 1. Barron Mountain Rock Cut

consisting of a nut and a bearing plate at the rock face (proximal end). Rock bolts were initially prestressed to 20 or 40 kips (90 or 180 kN) depending on the steel grade. The rock bolts are installed throughout the rock slope with the greatest concentration in the center section, near the andesite dyke, which is an area with an open seam and numerous open joints. Tendon elements are fully grouted with Portland cement grout, and the proximal ends are recessed into the rock mass. The tendons are passive elements, i.e. they were not prestressed, and there is no anchorage assembly. Most of the tendons are installed in three rows of a 10 ft X 10 ft (3.05 m X 3.05 m) grid pattern along the toe of the slope below the rock bench. Additional tendons are installed in the upper portion of the rock slope above the slide area.

Due to the different installation details including grout type, method of grouting, anchor head details, drill hole diameter, and the lengths of the reinforcements, we considered rock bolt and tendon reinforcements separately for the purpose of condition assessment. Grout type is an especially important detail. Portland cement based grout is alkaline and protects the steel reinforcement by passivating the steel as well as providing a barrier to moisture and oxygen. However, passivation of the steel may be compromised by the presence of chlorides or acidic conditions. Polyester resin grouts are neutral and do not passivate the steel. They protect the steel by creating a barrier. However, the rock bolts include an unprotected free-length and the amount of cover associated with the resin grout within the bonded zone is uncertain. Also, prestressing tends to cause resin grout to crack. One of the goals of the condition assessment is to study the integrity of the grouts with respect to providing a barrier surrounding the reinforcements, and the degree to which Portland cement grout is passivating the steel.

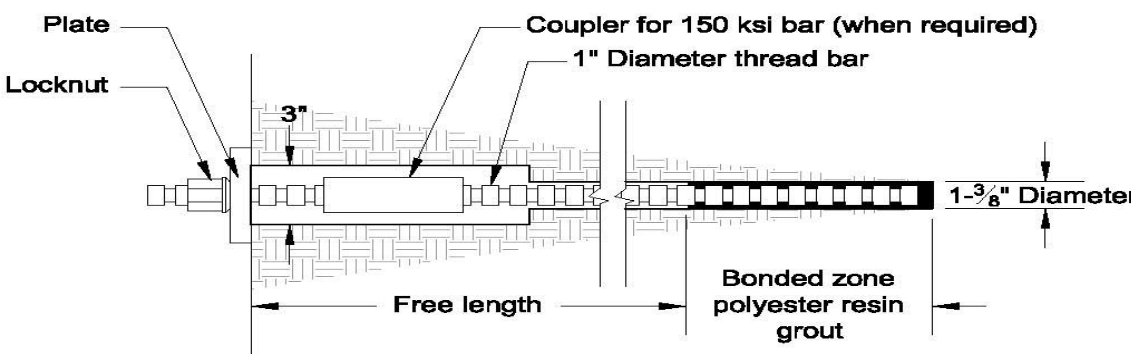


FIGURE 2. Rock Bolt Details

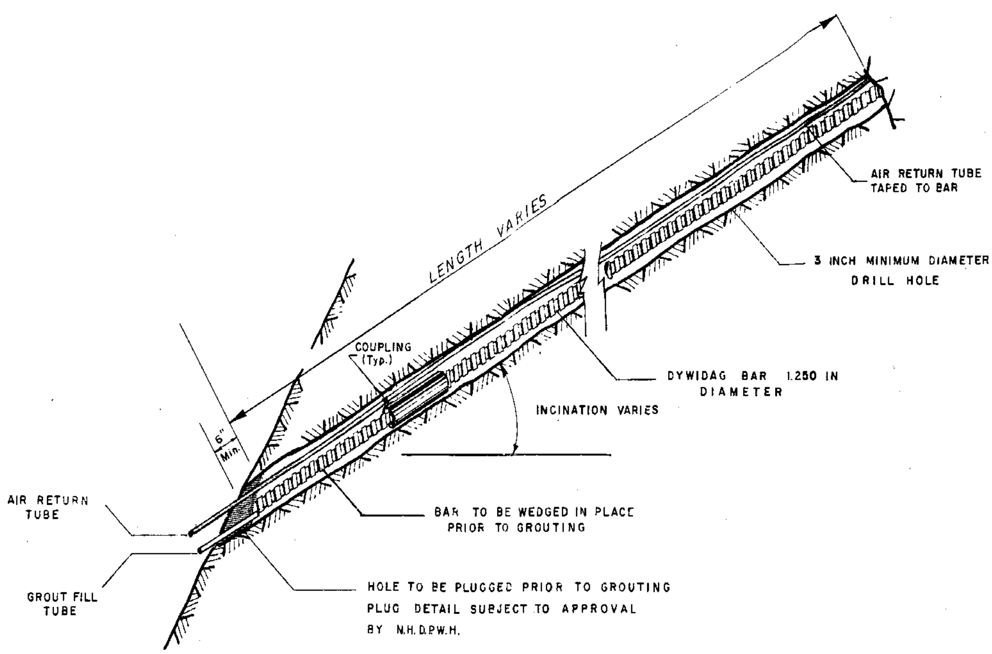


FIGURE 3. Detail of Rock Tendon (Haley and Aldrich, 1973)

SERVICE-LIFE ESTIMATE

Site Conditions

The first step in estimating the longevity of the rock reinforcement is to evaluate the corrosiveness of the rock mass and the vulnerability of the reinforcement to metal loss. Generally, moisture content, chloride and sulfate ion concentration, resistivity and pH are identified as the factors that most affect corrosion potential of metals underground. Quantitative guidelines are available for assessing the potential aggression posed by an underground environment relative to corrosion (FHWA, 1993).

Sampling and Testing of Rock & Groundwater

Five samples of weathered rock and groundwater were collected to evaluate the corrosiveness of the rockmass. The measured pH (4.2 to 6.2), resistivity (4000 Ω-cm to 9000 Ω-cm), and moisture conditions within the weathered rock correspond to an average corrosive environment. Measured sulfate and chloride ion concentrations (650 ppm and 720 ppm, respectively) are also at levels high enough to be conducive to an average corrosive environment. Sample locations RS-1, RS-4 and RS-5 are shown on Figure 4 describing the area where most of the NDT and invasive testing was performed. In general, higher salt concentrations are observed near the base of the rock cut. The corrosiveness classification at the site is between II and III, on a scale where "I" is considered highly corrosive and "IV" is slightly corrosive (FHWA, 1993). This rating is used to estimate the rate of metal loss anticipated over the service life of the reinforcements.

Service-life Estimate Based on Corrosiveness of Environment

The following equation, proposed by Romanoff (1957), is used to estimate corrosion rate and corresponding service life of buried metal reinforcements:

$$X = K \times t^r \tag{1}$$

where,

X = loss of reinforcement thickness or radius (μm)
K = constant (μm)
t = time (years)
r = constant

Equation (1) assumes that attack from the surrounding environment is immediate and unaffected by the presence of grout around the metal. Thus, the estimated metal loss is applicable to the unprotected, free length for the rock bolts, but is a conservative estimate for the bonded zone surrounded by grout and for the tendon elements passivated by Portland cement grout.

The appropriate parameters for use in the rate equation are based on the corrosiveness index of the weathered rock samples collected from the Barron Mountain site. According to the recommendations described in NCHRP (2002), the parameters "K" and "r" for use in the rate equation are adjusted relative to soil conditions as summarized below. In Table 1, the constant "r" is taken as one for simplicity, and considering the relatively short time frame (< 20 years) inherent to most of the observations used to develop the table.

TABLE 1. Recommended Parameters for Service Life Prediction Model (NCHRP, 2002)

Parameter	Average	Corrosive	Highly Corrosive
K (µm)	35	50	340
r	1.0	1.0	1.0

Based on the measurements of resistivity and pH, and the hydrogeologic conditions at the Barron Mountain site, the corrosiveness of the environment is described as between average and corrosive for the purpose of estimating service life (Classification II to III). Therefore, values of K = 35 µm to 50 µm and r = 1 will be used to estimate the loss of cross section and service life of rock bolts installed at the site. Thus, for the rock bolts, approximately 0.08 in (2 mm) to 0.118 (3 mm) of diameter corresponding to approximately 16% to 22% of the original cross section is expected to be consumed by corrosion after 30 years in service at Barron Mountain.

The tendon element cross sections do not include sacrificial thickness, and apparently, rely on the surrounding Portland cement grout to passivate and protect the steel from corrosion. Therefore, the service-life of these elements corresponds to the integrity and the thickness of grout surrounding the reinforcements. However, the possibility of chloride contamination of the Portland cement grout exists, which may depassivate the steel and initiate corrosion. The time for initiation of corrosion in the presence of chlorides depends on the concentration of chlorides at the grout/rock interface, and the diffusivity and thickness of the grout surrounding the tendon. If the bars are centrally located within the 3 in (76 mm) diameter drill holes, they are protected by approximately 0.875 in (22 mm) of grout. This amount of cover should provide at least 50 years of protection (since installation), considering the chloride concentrations measured from samples of grout and weathered rock obtained from the site.

NDT TESTING

The condition assessment consists of visual observations and analyses of results from nondestructive tests. Four NDT's are employed including measurement of half-cell potential, polarization current, impact and ultrasonic testing. Details of NDT including test procedures are described by NCHRP (2002).

Half-cell potential and polarization measurements are electrochemical tests, and the impact and ultrasonic techniques are mechanical tests involving observations of wave-propagation. In general, these NDT's are useful indicators of the following:

- Half-cell potential tests serve as an indicator of corrosion activity.
- Results from the polarization test are indicative of grout quality and degree of corrosion protection.
- Impact test results are useful to diagnose loss of prestress, assess grout quality and may indicate if the cross section is compromised from corrosion, or from a bend or kink in the bolt.
- Ultrasonic test results are useful for obtaining more detailed information about the condition of reinforcements within the first few feet from the proximal end of the reinforcement.

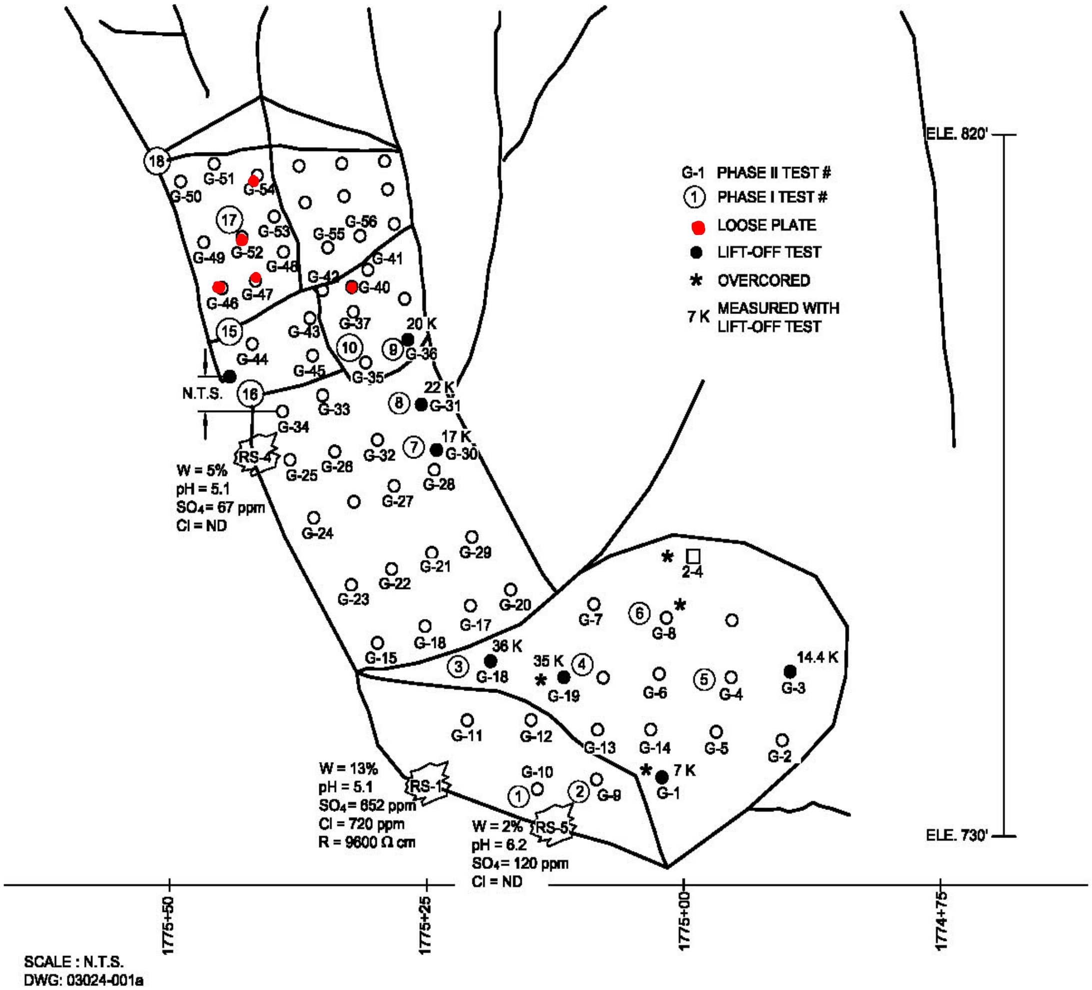


FIGURE 4. Rock Face Elevation View with Stationing, Reinforcement Locations and Test Numbers for Phase I and II.

INVASIVE TESTING

Invasive testing was conducted to verify the results from the nondestructive tests and the service-life estimates. The Phase II invasive Test Program includes some reinforcements with questionable condition, and some reinforcements considered to be in good condition, based on the results from NDT. Seven rock bolts were selected for lift-off tests and three rock bolts and one tendon element were over cored and sampled. Another rock bolt sample was retrieved when a loose block of rock was scaled from the face. Rock bolt and tendon locations included in the Phase II test program are located near Station 1775+00 and are identified in Figure 4.

COMPARISON OF NDT AND INVASIVE TEST RESULTS

Corrosion

Electrochemical measurements (half-cell potential and polarization resistance) are only able to assess the portion of the element in electrical contact with the surrounding electrolyte (rock mass). The ability of NDT to correctly identify the presence of corrosion along the grouted length was verified by invasive testing.

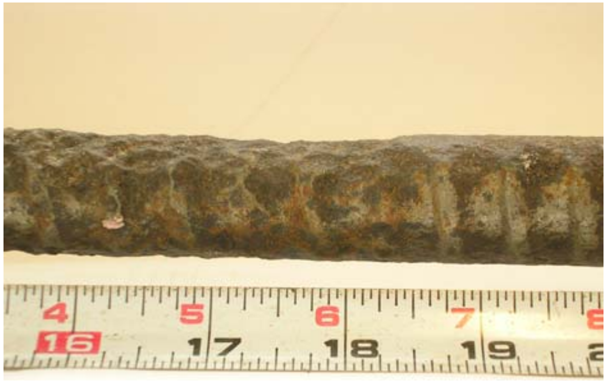
Bolt #6 and Tendon 2-4 (Figures 5 and 6) were the only exhumed samples that included grout that could be compared with electrochemical measurements included in the Phase I NDT. The half-cell potential and polarization measurements for Bolt #6 indicate that the element is likely corroded and the grout condition is questionable. The distal end of Bolt #6 did not appear to be completely surrounded with grout and corrosion was evident, which is consistent with the results from NDT.

Half-cell potential and polarization measurements for Tendon 2-4 also indicate that grout condition is questionable and that corrosion is likely. The measured porosity of the Portland cement grout is approximately 35%, which contributes to a high capacity for absorption of water and possible intrusion of chlorides. The high porosity observed for the exhumed grout sample tends to confirm the interpretation of grout quality from the results of NDT. Elevated levels of chloride were detected using the procedure described by AASHTO T 260, but the detected levels were still below 0.1% often associated with initiation of corrosion in reinforced concrete. Chlorides may be present along the rock face as a residue from salt spray produced from deicing of the highway. In general, the exhumed tendon element (Tendon 2-4), which was protected by Portland cement grout, was in very good condition compared to the resin grouted rock bolt (Rock bolt #6), and this is consistent with observations from NDT.

FIGURE 5. Rock Bolt # 6 With Resin Grout And Some Rust Staining Along Bonded Length.

FIGURE 6. Tendon Element 2-4 With Portland Cement Grout Retrieved Near Proximal End.

Loss of section from corrosion was observed behind the anchor plate, as shown in Figure 7(a), for three out of four rock bolt samples that were exhumed. This corrosion was not detected with electrochemical tests because the free lengths of the bolts were not in contact with the surrounding rock mass as shown schematically in Figure 2. Given the details of the anchor head assembly, reflections from a loss of section directly behind the anchor plate are difficult to identify from results of ultrasonic testing. This is because the data are masked by a strong reflection from the anchor head location. Approximately 20% loss of section is needed to produce a recognizable reflection and baseline measurements are needed to facilitate



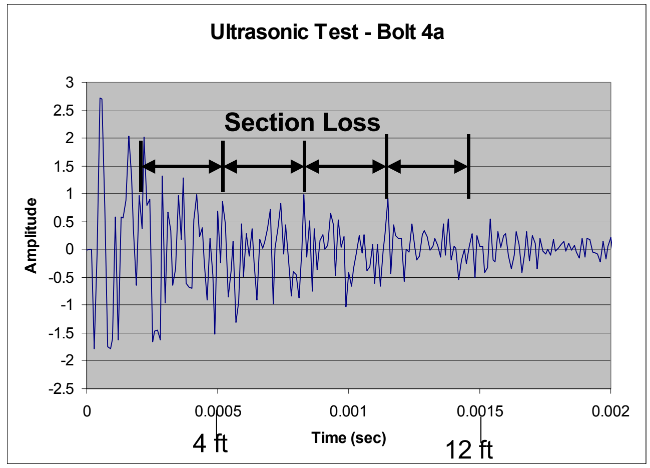


FIGURE 7a). Loss of Cross Section Observed Behind Bearing Plate for Bolt #4

FIGURE 7(b). Waveform form Ultrasonic Testing on Bolt #4.

interpretation of the signal, and to verify the measurement precision. Results from the ultrasonic test on Bolt #4 are shown in Figure 7(b) and a relatively subtle reflection approximately 2 ft (0.6 m) from the end of the element is evident corresponding to the area where significant loss of cross section (approximately 20%) is observed.

Specific Reinforcement Conditions

Generally, condition assessment of rock reinforcements utilizing NDT does not benefit from analysis of data to identify a specific feature along an element. Rather, the data are compared to one another to identify groups of responses that may be separated into either “good” or “questionable” condition. The interpretation is performed in terms of the character of the observed waveform including the initial rate of decay and the attenuation of the wave reflections. The sample domain is used as a guide to assess thresholds for “good” versus “questionable” condition. At the Barron Mountain site, loss of prestress is considered possible if the rate of signal decay is less than 80% after 1 ms. The strength of the reflected signal provides useful information about grout quality, and, in this sense, the quality of the signal is more relevant than the source of the reflections. Reflections with at least 20% of the original signal strength are considered poorly attenuated, and corresponding grout quality is suspect.

Impact test data from Bolt #6 included a relatively strong reflection from the distal end of the bolt corresponding to poor grout quality observed from the exhumed sample. Also, Bolt #16 was recovered when a loose block of rock was removed from the rock face. The results from analysis of the fracture surface were consistent with occurrence of stress corrosion cracking. Evaluation of test data from Bolt #16, indicates that a preexisting fracture surface at 4 ft (1.2 m) from the proximal end of the bolt may be evident in the impact test data. However, these reflections are very subtle and could easily be overlooked without knowledge of the existence of this fracture surface.

Reflections were observed from two of the reinforcements where couplings were retrieved, and often reflections were observed where rock joints or seams intercepted the grout body. These reflections could be misinterpreted as a loss of cross section, or other distress, in the absence of prior knowledge of coupler or rock joint locations.

Prestress

Table 2 is a summary of lift off test results and comparison with the interpretation from NDT. Damping, or the rate of decay, of acceleration amplitude response observed from an impact test has been shown to increase with respect to level of prestress for rock bolts (Rodger et al., 1997). Loss of prestress is diagnosed from NDT by comparing the rate of decay observed for the sample population and identifying rock bolts associated with relatively low rates of decay as having an apparent loss of prestress. Thus, NDT results are described in terms of "Good" or no good "NG", which correspond respectively to no apparent loss of prestress and apparent loss of prestress.

Reasonable agreement was recognized between results of lift-off tests and NDT. In general, the results indicate that a high percentage of the rock bolts have suffered loss of prestress. The comparison between NDT and lift-off test results is favorable for between 63% (5 of 8) and 88% (7 of 8) of the measurements. Some ambiguity exists with respect to interpretation of NDT results when an intermediate level of prestress remains, and this is apparent in the interpretation of results for Bolt #7. Large losses of prestress, or, at the other extreme, rock bolts with the majority of prestress remaining were correctly identified from the results of NDT.

TABLE 2. Lift-Off Test Results

Bolt #	Lift-Off (Kips)	NDT Result	Correct NDT
3	36	Good	Y
4	38	Good	Y
7	17	Good (?)	N(?)
8	22	Good	N
9	20	NG	Y
G-1	7	NG	Y
6	Loose	NG	Y
17	Loose	G/NG	Y(?)

SERVICE-LIFE ESTIMATE COMPARED TO METAL LOSS

Pits and craters were observed at a number of locations along the rock bolt samples, and craters appear to coalesce into areas of uniform corrosion extending for lengths of approximately 4 in (102 mm) (Figure 7(a)). Pit depth measurements were obtained at 178 locations along the surface of the rock bolt samples. Pit depths were measured with a pit depth gage having a sensitivity of 0.0001 in (2.5 μm). The average measured pit depth was approximately 0.015 in (0.38 mm) with a standard deviation of 0.014. The maximum measured pit depth was 0.1 in (2.5 mm) and 10% of the measured pit depths were greater than 0.031 in (0.79 mm). We observed that deeper pits were often associated with larger pit diameters, supporting the notion that pitted areas coalesce into areas of uniform corrosion.

Three of the rock bolt specimens exhibited a maximum loss of section corresponding to approximately 0.1 in (2.5 mm) in diameter. This loss is consistent with existing mathematical models of service-life and with the observation from NDT that 70% of the rock bolts have experienced significant corrosion. Considering the initial diameter, level of prestress, and rate of metal-loss we estimate that rock bolts will not become overstressed from loss of section due to corrosion for another fifteen to twenty years.

CONCLUSION

The objective of this project was to assess the condition and determine the remaining service life of the rock reinforcement at Barron Mountain. The results of the two-phased research study, consisting of NDT and invasive techniques, would be utilized to develop an action plan to retrofit, replace and extend the life of the reinforcement.

Tendons appear to be in better condition compared to rock bolts. Rock bolts have suffered a loss of prestress and some corrosion is evident. Tendons are fully grouted, passive elements and their useful life depends on the durability and integrity of the surrounding grout. The rock bolts are prestressed and are essentially end point anchorages. The useful life of the rock bolts depends on the durability of steel, grout and conditions at the anchorage. Thus, with respect to impacts on service-life, the rock bolts at this site are more vulnerable than the tendon reinforcements.

With respect to the rock bolts, corrosion is present, but the rate of metal loss appears to be close to expectations, and was apparently considered in the original design and corresponding selection of reinforcements and levels of prestress. The most severe corrosion of rock bolts was observed within 2 ft (0.6 m) of the anchor plate and this observation is consistent with those reported by FIP (1986). Tendon elements appear to be passivated by the alkaline conditions provided by the Portland cement grout. In spite of the apparently high porosity, the grout appears to have protected the steel from significant corrosion to date. The alkaline environment of the grout is apparently sufficient to protect the steel, but some corrosion may be possible due an ample supply of oxygen near the rock face, and the possibility of moisture and chloride intrusion. However, given the high porosity of the grout observed from the samples, chloride intrusion is a concern.

Compared to loss of service from corrosion, results from the condition assessment revealed that loss of prestress is the bigger concern relative to remaining service-life. The condition assessment also revealed locations of increased corrosion activity. Thus, a sound technical basis is established for planning future maintenance and rehabilitation activities at the site, ultimately resulting in a cost savings to the NHDOT.

Rock bolts should be load tested with proof and performance tests as described by PTI (1996) to demonstrate that adequate bond strength exists. Bolts passing the load test should be re-stressed to the design load, and those not passing the load test should be replaced. Rock bolts are apparently losing prestress over time and some differences were noted within the course of a year.

Placement of corrosion protection (grout) along the free length of existing rock bolts should be considered and may allow a greater remaining service life for the rock bolts subsequent to remediation. Provisions need to be included within the corrosion protection system so as not to restrict movement along the free length, because rock bolts may need to be restressed in the future. Benefits include protection of the rock bolt surface area behind the anchor plate where the most severe corrosion is observed. It may also be possible to monitor corrosion activity separately along the grouted free length, and along the bond length if they are electrically isolated from one another. These data will be useful to justify extending the expected service life of the system as performance data is collected and analyzed. Thus, increased benefits from remediating and retrofitting the reinforcement system may be realized.

Rock bolts have an estimated remaining service life of approximately 20 years due to corrosion. Presently the service-life is limited by the existence of an unprotected free length. The veracity of the remaining service life estimate for the restressed bolts should be confirmed by corrosion monitoring at approximately 10-year intervals. Future corrosion monitoring should include electrochemical tests (half-cell potential and polarization current) to check for the presence of corrosion, and wave propagation techniques (impact and ultrasonic tests) to check for loss of cross section, particularly near the backside of the anchor plate.

Considering the possibility of chloride intrusion into the Portland cement grout, we recommend that passive tendon elements be monitored at approximately 5-year intervals to check the veracity of the remaining service life estimate. Monitoring should include measurement of half-cell potential to document that these are still in the range associated with passivated steel elements. If the measured half- cell potentials are below -350 mV, then further evaluation and remediation, or replacement, of these elements may become necessary.

Specific activities are recommended to address the longevity concerns of the rock reinforcement and to insure the long-term stability of the rock slope at Barron Mountain. The critical tasks and recommended time periods are identified in the following action plan:

- Annual monitoring of strain gages installed on two replacement tendons
- NDT testing of tendons at 5-year intervals
- Prior to the year 2010 – load test each rock bolt; re-stress passing bolts; install bolts at new locations where crack have developed
- Corrosion monitoring (NDT tests) of re-stressed bolts at 10-year intervals.

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