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6 pages | | PAPERBACK
ISBN 978-0-309-21347-9 | DOI 10.17226/14587

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October 2011

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Responsible Senior Program Officer: E. T. Harrigan

Research Results Digest 364

VALIDATION OF LRFD METAL LOSS AND SERVICE-LIFE STRENGTH REDUCTION FACTORS FOR METAL-REINFORCED SYSTEMS

This digest summarizes key findings of NCHRP Project 24-28A, "Validate the Results of NCHRP Project 24-28," conducted by McMahon & Mann Consulting Engineers, P.C., under the direction of the principal investigator, Kenneth L. Fishman. The digest is based on the project final report authored by Dr. Fishman. The full text of the project final report is available for download at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=727.

INTRODUCTION

This digest summarizes the results of research conducted as a follow-up to NCHRP Project 24-28, "LRFD Metal Loss and Service-Life Strength Reduction Factors for Metal Reinforcements in Geotechnical Applications." NCHRP Project 24-28 assessed and improved models for corrosion potential, metal loss, and service life of metal-reinforced systems used in retaining walls, and highway cuts and fills. The project compiled a performance database for earth reinforcements that describes the existing conditions and measured corrosion rates of in-service reinforcements at approximately 170 sites across the United States and Europe. Data were obtained from reinforcement types typical of mechanically stabilized earth systems (MSES) as well as installations of rock bolts and ground anchors. These data were used to identify and group trends related to the character of the fill or in-situ earth materials, reinforcement type, and various site conditions. Based on these trends, the reliability of metal-loss modeling and service-life predictions were computed and the corresponding biases with respect to nominal tensile strengths used in design were evaluated and then used to calibrate appropriate resistance factors for use in load and resistance factor design (LRFD). The results, findings, and conclusions of NCHRP Project 24-28 were published as *NCHRP Report 675: LRFD Metal Loss and Service-Life Strength Reduction Factors for Metal-Reinforced Systems.*[1]

MSES reinforcements consist of galvanized steel strips, mats, or grids. The possibility of metal loss is considered in design through selection of fill materials that are relatively nonaggressive, and the use of sacrificial steel in the reinforcement cross section. NCHRP Project 24-28 found that estimates of sacrificial steel requirements and remaining strength were reliable for reinforcements surrounded by high- or good-quality fill materials. However, the performance estimates for reinforcements in marginal-quality fills were highly uncertain. Also, the estimated performance of galvanized reinforcements after the base steel was exposed by depletion of the zinc coating was subjective due to a lack of data from older installations. This situation could

[1]Available for download at http://www.trb.org/Main/Blurbs/165158.aspx.

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lead to overly conservative service-life estimates and recommendations of resistance factors for use in LRFD that are potentially too low.

Rock bolts, soil nails, and ground anchors have features that differ from those of MSES reinforcements, including components of single or double corrosion protection systems and the use of high-strength steel elements that are often pre-stressed during installation (soil nails are not pre-stressed). Thus, the performance and service lives of these types of earth reinforcements are influenced by the installation details, the existing conditions of elements incorporated into the corrosion protection systems, and localized forms of corrosion such as stress crack corrosion or hydrogen embrittlement rather than uniform or general corrosion. Better information on the in-service conditions of rock bolts, soil nails, and ground anchors is needed to assess factors that may significantly affect their performance. Since construction records are often not available from rock bolt installations, information from in-service reinforcements is needed relative to the geometry and quality of these installations.

NCHRP Project 24-28 included proposals for future research to (1) address the high uncertainty regarding the performance of MSES reinforcements in marginal quality fills, (2) obtain additional performance data from older installations of MSES reinforcements, and (3) implement more robust test techniques to obtain better information about the existing conditions of rock bolts, soil nails, and ground anchors. This digest summarizes results from NCHRP Project 24-28A, which addressed these proposals and further validated the results from NCHRP Project 24-28, including predictive models for corrosion potential, metal loss, and service life of metal reinforced systems. The complete project final report for NCHRP Project 24-28A is available for download.[2]

RESEARCH APPROACH

Marginal quality fills are classified according to minimum laboratory resistivity (AASHTO T 288, "Determining Minimum Laboratory Soil Resistivity"), which values can be very different from values measured in situ. Samples of fill for resistivity testing are often collected prior to construction from stockpiles representing potential sources of fill material. However, sources actually used for construction are uncertain. Therefore, the variability inherent to the observed performance of marginal fills is likely due to uncertainty with respect to the fill properties, which may also be inherently variable. These effects are not as prevalent for good or high quality fills wherein sources of materials are more certain, variability is less, and the rate of metal loss is not as sensitive to changes in fill resistance. Therefore, the approach to reducing the uncertainty with respect to performance of marginal quality fills is to obtain better measurements of fill resistivity, and corresponding correlations with measurements of corrosion rate. Thus, there is a need to identify and implement methods to measure fill properties at the time and location of the corrosion rate measurements.

For rock bolts, soil nails, and ground anchors there is a need to extract more information on their existing condition. Testing and data analysis techniques must be refined to fill this need. Other research has applied the impulse response (IR) technique to study the condition of deep foundation elements, and these results have been useful in locating and identifying the size and shape of anomalies along concrete-drilled shafts. This is considered an improvement over the sonic echo (SE) technique, which is the existing practice for condition assessment of rock bolts. The SE technique is only useful in identifying the locations of sources of reflections and providing qualitative information about pre-stress levels. Thus, the suitability of the IR test for rock bolt installations was explored as part of NCHRP Project 24-28A.

NCHRP Project 24-28A included the following tasks:

1. Evaluate the effectiveness of the impulse response technique in determining the in-situ condition of rock bolt installations. An important component of this task was the installation and testing of "dummy" rock bolts incorporating planned anomalies to provide a basis for comparison.
2. Identify methods to determine resistivity for in-situ materials surrounding earth reinforcements at the same time and location as corrosion rate measurements. An important part of this task was to verify these methods by constructing an earth embankment that incorporated earth reinforcements, conducting testing of the reinforcements, and comparing the

[2] http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=727

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test results with those found under known conditions.

3. Further verify the test methods and relationships developed in Task 2 through field testing. This was accomplished through measurements of corrosion rates and resistivity from sites with marginal fills where fill samples could be retrieved and tested for resistivity using a standard test box as a basis of comparison.
4. Obtain field data from older sites to evaluate the long-term performance of base steel subsequent to depletion of zinc coating from older in-service reinforcements.

FINDINGS

Resistivity Measurements

The linear polarization resistance (LPR) technique has been used to determine the corrosion rate of in-service earth reinforcements. A three-electrode configuration is commonly employed whereby a current is impressed between two in-service reinforcements that serve as the working and counter electrodes, and the surface potential of the working electrode is measured with respect to a half-cell that serves as the reference electrode. The earth material surrounding the working electrode (earth reinforcement under test) serves as an electrolyte and measurements of polarization resistance must be corrected to consider the effects of this additional impedance. Current practice is to measure the resistance of the earth material via an AC impedance technique immediately following the DC polarization measurements. Results from this project demonstrate that earth resistivity (ρ) can be computed from measurements of earth resistance as:

$$\rho = \frac{2 \times \pi \times L \times R}{\left[\ln\left(\frac{8 \times L}{D}\right) - 1\right]} \quad (1)$$

where L and D are the electrode length and diameter, respectively, and R is the measured earth resistance. This very simple expression appears to render good results in most cases. Thus, measurements of earth resistivity can be made at the same time and location as corrosion rate measurements for earth reinforcements.

A test embankment was constructed to verify the use of Equation 1 for relating the measured fill (earth) resistance to resistivity. The embankment was split into two sections, each with a different fill material of known resistivity. Different reinforcement types, sizes, and shapes were installed and the spacing between the reinforcements was varied. Measurements from the test embankment and use of Equation 1 yielded values of ρ that were in reasonable agreement with the known values of resistivity as long as the reinforcements were located at least 2 feet away from the surface of the embankment. On average, resistivities computed with Equation 1 were within 10 to 20 percent of the known values.

Field Monitoring of MSES

Equation 1 was further verified via data from testing in-service MSES reinforcements at sites located in California under the jurisdiction of Caltrans. Five sites were included in the field investigation with ages of reinforcements that ranged between 5 and 39 years old. In-situ measurements of resistivity were obtained from the three-electrode, AC impedance technique and use of Equation 1. Additionally, samples of fill material were retrieved through access holes penetrating the precast concrete wall face units and tested for resistivity via a soil box similar to that described in AASHTO T 288. The latter test results served as a basis for comparison with in-situ measurements of resistivity. Reasonable results were obtained wherein in-situ testing rendered a range of results that was consistent with baseline values obtained from samples tested in the soil box. Furthermore, corrosion rate measurements were negatively correlated with resistivity (i.e., higher corrosion rates were associated with lower resistivity). Thus, results from corrosion rate measurements correlated very well with in-situ measurements of resistivity.

This fieldwork included the oldest MSE wall in the United States, which was constructed in 1971, along Route 39 through the San Gabriel Mountains near Los Angeles, and was 39 years old at the time when observations were made. Reinforcements unearthed from this site appeared to be in excellent condition with no significant metal loss, although base steel was exposed in some locations. Observed corrosion rates were less than those anticipated from the current metal-loss rates suggested by AASHTO for MSES design. These data suggest that the benefits of galvanization are realized for much longer than the 16 years implied by the current edition of the AASHTO LRFD Bridge Design Specifications.

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Thus, measurements of corrosion rate obtained from the Route 39 site are extremely interesting and are some of the first confirmed observations of the rate of steel consumption subsequent to depletion of zinc for galvanized reinforcements used in MSE construction in the United States. These rates are much less than those used in design and appear to be closer to the corrosion rates used for zinc, suggesting that a discrete change in corrosion rates as zinc is depleted, as implied by the current AASHTO model for metal loss of MSE reinforcements, does not necessarily occur.

Implementation of Impulse Response Test for NDT of Rock Bolts

The impulse response test (IR) is used for probing the lengths of rock bolts to access details of the installation and conditions surrounding the structural elements (i.e., steel rods). The IR test involves application of an impact to the free end of the rock bolts with an instrumented hammer and measurement of the response of the element with a transducer attached near the point of impact. Measurements of the impact force and the resulting response are processed in the frequency domain. A mobility curve is obtained by dividing the velocity response spectrum by the force spectrum, and incorporates a range of frequencies corresponding to the energy content of the impact (0–4000 Hz). The initial slope of the mobility plot yields the dynamic stiffness of the system, and the frequency of the peaks at resonance describes the geometry. By comparison, the SE test does not require an instrumented hammer, and only involves measuring the response of the rock bolt after impact, which is presented in the time domain.

The mobility curve yields the impedance of the rock bolt corresponding to the material properties and geometry of the installation. The impedance of the rock bolt is related to the geometric mean of the heights of the resonant peaks in the portion of the mobility curve where the shaft response is in resonance. Mobility is related to impedance as (Davis and Robertson, 1975)

$$N = \frac{1}{\rho \times V_p \times A} \tag{2}$$

where ρ is mass density = 4.66 (lb*s^2/ft^4) for grouted rock bolts, V_p is compression wave velocity = 12,000 ft/s for grouted rock bolts, and A is the cross-sectional area corresponding to the resonant portion of the mobility plot. Thus, the cross-sectional area corresponding to the resonant portion of the mobility plot can be determined from measurements of cyclic mobility and knowledge of the density and compression wave velocity of the grout surrounding the earth reinforcement.

The utility of the IR test was evaluated by testing six dummy rock bolts installed in cooperation with the New Hampshire Department of Transportation at the site of the Barron Mountain Rock Cut along I-93 near Woodstock, NH. Dummy rock bolts were installed using materials and techniques similar to actual rock bolt installations. Installations varied with respect to geometry including the free lengths, bonded lengths, and total lengths of the rock bolts. One-half of the installations were "normal"; the other half had known defects including reduced cross-sections, breached sheathing along the free length, or voids in the grout along the bonded lengths.

The SE and IR tests were applied to the dummy rock bolts, and the validity of the results was confirmed based on comparisons with known conditions. Results from both the IR test and the SE test rendered useful information for condition assessment. Levels of pre-stress were interpreted from SE test results in qualitative terms as high, moderate, or relatively low, based on a comparison of results between samples. This capability has been recognized previously, and the results from the IR do not offer any improvements in this regard. Clear reflections were apparent from the interfaces between the free lengths and the bonded zones, such that results from the SE test were useful to identify the free lengths of the test elements. However, details of anomalies and conditions within the bonded zones were difficult to discern, or not discernable, from results of SE testing. Important features of the installations were more apparent from the IR test results, compared with the SE test results, including:

1. Interfaces between bonded and unbonded zones are more distinct.
2. Details and conditions within the bonded zone are apparent in the results from the IR test, which cannot be discerned from the results of SE testing.
3. Mobility plots are affected by anomalies in terms of distinct reductions in the energy (peaks) and frequencies at resonance. This is due to the energy loss from additional wave reflections caused by the anomalies, and cor-

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responding reductions in the propagation velocities for compression waves traveling within the grout.

4. The cross-sectional areas of the elements at the sources of reflections were observed from results of IR testing, which are obtained from the mobility at resonance.

CONCLUSIONS

This project addressed proposals made in NCHRP Project 24-28 to (1) obtain more reliable data and reduce uncertainty with respect to the performance of MSES constructed with marginal quality fills; (2) obtain additional performance data from older installations of MSES reinforcements; and (3) implement more robust test techniques to evaluate the existing conditions of rock bolts, soil nails, and ground anchors. Results presented herein serve to further validate results from NCHRP 24-28 and the predictive models for corrosion potential, metal loss, and service life of metal-reinforced systems developed therein.

1. The variability of the performance of marginal fills observed in NCHRP Project 24-28 is due to uncertainty with respect to the fill properties, which may also be inherently variable. Measurements of fill resistivity obtained at the location and time of corrosion rate measurements reduce this uncertainty and improve the ability to model the performance of MSES constructed with marginal quality fills. Results presented in this report demonstrate that the resistivity of in-situ materials surrounding earth reinforcements can be determined at the time and location of corrosion rate measurements. The technique employs measurements of resistance via the three-electrode technique, and a simple relationship between the measured resistance and resistivity. Measurements of corrosion rate and resistivity in the three-electrode configuration are most useful, since the majority of measurements in the database compiled as part of NCHRP Project 24-28 utilize this technique. Thus, resistivity is computed using the measured resistance, and the width and length of the reinforcement. This technique was verified via measurements under known conditions within a test embankment, and data collected from five different sites in California with access to MSE reinforcements and fill materials for sampling and testing.
2. The fieldwork included the oldest MSE wall in the United States, which was constructed in 1971, along Route 39 through the San Gabriel Mountains near Los Angeles, and was 39 years old at the time when observations were made. Measurements of corrosion rate obtained from this MSE wall are extremely interesting because they are some of the first confirmed observations of the rate of steel consumption subsequent to depletion of zinc coating of galvanized reinforcements used in MSE construction in the United States. These observed rates are much less than those used in design and appear to be closer to the corrosion rates used for zinc, suggesting that a discrete change in corrosion rates as zinc is depleted—as is implicit in the current AASHTO model for metal loss of MSE reinforcements—does not necessarily occur.
3. The impulse response test was implemented for probing the lengths of rock bolts to access details of the installation and conditions surrounding the structural elements (i.e., steel rods). The IR test is useful to locate and identify the size and shape of anomalies along rock bolt installations. This test is considered an improvement over the sonic echo technique, which is the existing practice for condition assessment of rock bolts. Results from the IR test were verified through tests performed with dummy rock bolts that included both typical and deliberately distressed installations. Results from this study indicate that the IR test is more robust and renders additional information for condition assessment of rock bolts compared to what is achievable from the SE test. However, the SE test is adequate to assess remaining levels of pre-stress, and to identify the free lengths of rock bolt installations. Knowledge of the free length is useful if the total length is known, and general details of the installation are needed for correlating data from further electrochemical testing (e.g., lengths are needed to assess surface areas of the test elements and correlate corrosion rates from LPR measurements).

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PROPOSALS FOR POSSIBLE FUTURE RESEARCH

1. The techniques for measuring fill resistivity implemented in this study should be applied to the database developed for NCHRP Project 24-28 to develop service-life models that directly incorporate fill resistivity as a variable. Current service-life models used to calibrate LRFD strength-reduction factors in NCHRP Project 24-28 apply to relatively broad ranges of fill types (resistivities) leading to wide scatter and variability within the range of marginal quality fills. Service-life models that directly incorporate fill quality will yield improved correlations between corrosion rate and fill resistivity, and improvements to reliability-based calibration of LRFD strength-reduction factors for MSES constructed with marginal quality fills.
2. More data should be collected to document the performance of MSES constructed with marginal quality fills. The characteristics of marginal quality fill including salt contents and resistivities may vary randomly with respect to location within a given source. Fill resistivity may change over time due to changes in moisture content, salt concentration, etc., and these changes are not described by measurements on fill sources obtained prior to construction. Thus, data should be collected from selected sites at prescribed intervals to monitor spatial variations and the effects of changes in conditions that may occur over time. These data would be useful to provide guidance, recommendations, specifications, and limitations on use of marginal quality fills for construction involving earth reinforcements.
3. The IR test is recommended for condition assessment of rock bolts when more detailed information from within the bonded zone is necessary. Further evaluations should be conducted for rock bolt lengths greater than 20 feet.
4. Additional data on the performance of rock bolts should be collected and used to develop fragility curves to describe the time-dependent vulnerability and safety of rock cuts that are supported with rock bolts.

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ISBN 978-0-309-21347-9
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