Geotechnical Asset Management with Performance Data from MSE Steel Reinforcements

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ABSTRACT: Asset management enables decisions with due consideration to expected performance, service life, maintenance, rehabilitation or retrofit, and associated lifecycle costs. Performance data make an important contribution to asset management as a means to quantify service life including the effects of time, climate, site conditions, alternative materials, and the benefits of maintenance and rehabilitation. Earth reinforcements, including soil reinforcements, rock bolts, soil nails and ground anchors, are important geotechnical components often used to support embankments, cuts, slopes, retaining walls, as well as bridge approaches, abutments and wing walls. Protocols have been developed for condition assessment and performance monitoring of earth reinforcements. The corresponding data are used to document past performance, and develop models to forecast future performance and compute expected service lives. This paper describes techniques to collect and model performance data, and specific applications of Geotechnical Asset Management (GAM) to a highway system.

INTRODUCTION

Asset management is an important issue facing highway operations, and forecasting the needs for maintenance, retrofit or replacement of existing facilities are necessary components of Transportation Asset Management (TAM). Mechanically Stabilized Earth (MSE) structures have been constructed in the United States using galvanized steel soil reinforcements since 1971, and currently there are more than 40,000 MSE structures with steel reinforcements distributed throughout the United States (AMSE, 2006). MSE structures should be included in a TAM program along with pavements, bridges, ancillary structures, etc., to help ensure optimal usage of limited resources (FHWA, 2008).

As part of a TAM strategy data are collected to document the performance of MSE structures including the condition of metallic reinforcements and corresponding rates of metal loss. Performance data are useful to identify when, or if, accelerated corrosion is occurring, and can help transportation agencies decide on the most appropriate course of action when conditions are deemed to be unfavorable. This paper describes a performance database useful for asset management, test techniques and protocols that are being employed to collect performance data for earth reinforcements, and applications including evaluation of life cycle costs associated with use of alternative materials, and use of monitoring to manage risk and uncertainty with respect to expected service life.

OVERVIEW OF PERFORMANCE MONITORING

The benefits of condition assessment and corrosion monitoring are to provide better estimates of expected service life, and to identify conditions where service life may be compromised. Corrosion monitoring programs and monitoring of earth reinforcements may be implemented with the following objectives for TAM (Elias et al. 2009):

- Assess the validity of the design corrosion rates used in the design of earth reinforcements.
- Evaluate how service life and sacrificial steel requirements may be affected by selection of fill sources and QA/QC during placement and compaction of fills.
- Identify the impact of contaminants on service life and performance, e.g. if there is a suspicion that the groundwater regime established in the structure during service is acidic, highly alkaline, or contaminated with salts.
- Provide a means to warn of impending failure in response to some visible distress in the MSE structure, and for structures of critical importance.
- Identify how particular climatic conditions may affect service life, e.g. structures in or adjacent to marine environments.
- Evaluate the effects from extreme events on service life, e.g. hurricane induced tidal surges may inundate structures constructed in estuary environments (e.g., Sagues et al., 1998).

DATA COLLECTION

The subsurface environment surrounding the elements must be characterized in terms of fill source, moisture conditions, presence of organics, and electrochemical parameters known to contribute to corrosiveness. Generally, moisture content, chloride and sulfate ion concentration, resistivity and pH are identified as the factors that most affect corrosion potential of metals underground (AASHTO, 2012). Details for collecting, testing and evaluating soil and groundwater samples are described in the recommended practices prepared by Withiam, et al. (2002) and Elias, et al. (2009).

Several nondestructive tests are available for corrosion monitoring including measurements of half-cell potential (E_{corr}), linear polarization resistance (LPR), and electrochemical impedance spectrometry (Lawson et al., 1993). With these techniques, a large number of frequent samples may be obtained. Because the tests are nondestructive, reinforcements are left intact and in service after testing, and available for future monitoring. These techniques are capable of measuring in situ corrosion rates of galvanized steel, and metal losses are inferred from these measurements. Elias et al. (2009) and Fishman and Withiam (2011) describe these techniques in detail including the linear polarization technique (LPR). The test techniques and procedures described in these reports have been researched and developed over the past several decades (Lawson et al. 1993). These electrochemical test techniques and test protocols are mature technologies, and serve as useful tools for collecting performance data and performance management.

Direct visual observations can be made on the exposed portions of the earth reinforcements, and readings of half-cell potential and corrosion rate are collected from in-service reinforcements that are wired for monitoring, and from coupons installed within the wall fill (Elias et al., 2009). Direct observations and measurements of half cell potential render information on the existing condition of reinforcements including the extent and distribution of metal loss (including zinc and base steel) that may be compared to expectations and corresponding measurements of corrosion rate. Direct observations of in service reinforcements may be obtained via core holes advanced through the wall facing or from shallow excavations near the surface along the top of the wall. In some cases coupons are placed during construction that may be retrieved for observations at selected intervals during the design life of the wall.

PERFORMANCE DATABASE

Performance data are included from 170 sites located throughout the United States and Europe as described by Fishman and Withiam (2011). Data have been collected and archived from sites located in the Northeast, mid-Atlantic, Southeast, Southwest and Western United States. Performance data include direct observations of metal loss, measurements of remaining tensile strength, and results from electrochemical tests including linear polarization resistance (LPR) measurements.

Data incorporate a range of fill conditions denoted as high and good quality, and spatial and temporal distributions of measurements. High and good quality fills both meet AASHTO specifications for MSE design and construction; but high quality fills are described as having minimum resistivity measured in the lab (ρ_{min}) greater than 10,000 Ω-cm, and good quality fills have 3000 Ω-cm < ρ_{min} < 10,000 Ω-cm. These fill groupings are selected considering (1) that most MSE walls are designed and constructed following specifications similar to AASHTO, which requires fill materials to have ρ_{min} > 3000 Ω-cm, and (2) review of existing inventories (AMSE, 2006) that indicate more than 50 percent of MSE walls constructed in the United States and Europe over the past 30 to 40 years incorporate fill materials having ρ_{min} > 10,000 Ω-cm.

In addition to fill quality, data are partitioned with respect to the time in service. Data are organized into two groups that include measurements from reinforcements with less than, and more than two years in service. This is consistent with observations and current metal loss models (e.g. AASHTO) that recognize corrosion rates attenuate with respect to time.

In general, the database is self-contained yet structured such that it can be ported to other existing databases**.** Information within the shell of the database is distributed amongst seven distinct tables comprising a total of 150 data fields. The database includes the following tables:

- Project
- Walls/Structure
- Reinforcements
- Backfill/Subsurface
- Observation Points
- NDT Results
- Direct Observations

These categories of information are similar to those employed within other databases that are based on the FHWA Bridge Management Inventory (Timmerman, 1990; Wheeler, 2001; Hearn et al., 2004; Beckham et al., 2005; AMSE, 2006).

FILL SELECTION AND GAM

One aspect of highway asset management involves quantifying the effects of alternative sources of fill materials on the performance and expected service lives of MSE walls reinforced with galvanized steel reinforcements. Fill sources can have a significant effect on performance, and can compound the needs for controlling infiltration and surface drainage. Furthermore, fill quality affects sacrificial steel and service life requirements. Existing performance data are partitioned with respect to the quality and character of fill materials used for construction of MSE walls and reliability analysis is applied to service life modeling. The objective is to achieve the same expected service life regardless of the fill source. This is accomplished by adjusting the amount of sacrificial steel included in the design of the reinforcements in consideration of the fill source.

A reliability-based approach is used to quantify the impact of alternative sources of fill on expected service life. The strength limit state considered for design of metallic reinforcements ensures that reinforcements maintain enough yield resistance to keep the probability of yielding below acceptable limits throughout the service life of the facility. Service life is affected by the amount of sacrificial steel included in the reinforcement cross section, and sacrificial steel requirements are computed via metal loss models that are incorporated into specifications for the design of MSE walls. Thus, various metal loss models are proposed considering alternative fills. The target reliability is selected on the basis of past performance and target levels of reliability commonly associated with load and resistance factor design (LRFD).

Performance is described in terms of the probability (p_f) that a given design condition or design limit state may not be satisfied. One of the design conditions involves the loss of section (i.e. the remaining cross section) due to corrosion at the end of the intended service life, and the applicable design limit state is such that the tensile loads transferred to the reinforcements shall not exceed the rupture resistance of the reinforcements at any time during the intended service life.

A reliability analysis is performed to compute p_f that involves the following steps:

1. Model data trends; e.g., in terms of time, location and fill characteristics
2. Model the data distribution, e.g. normal, log normal, Weibull, etc.
3. Select statistics for reliability analysis, e.g., mean and standard deviation.
4. Compute p_f considering the data trends, distribution and corresponding statistics.

Trends in the data are identified with respect to fill quality and age of the reinforcements. Trends are modeled by partitioning the data into corresponding groups. These groups include high quality fills, good quality fills, galvanized reinforcements before zinc coating is consumed with ages less than or greater than two years old, and galvanized reinforcements after the zinc coating has been consumed. Statistics describing observations of corrosion rate from these groups are described in Table 1. These data apply to galvanized steel reinforcements whereby v_{g1} is the corrosion rate of zinc during the first two years of service, v_{g2} is the corrosion rate of zinc after the first two years, and v_s is the corrosion rate of base steel subsequent to the consumption of the zinc layer from the surface. Data distributions are modeled as lognormal, which is tested for fitness as described by Fishman and Withiam (2011).

Table 1. Statistics Describing the Performance of Reinforcements in High Quality or Good Quality Fills[1]

Corrosion Rate Parameters	High Quality		Good Quality	
	μ (μm/yr)	σ (μm/yr)	μ (μm/yr)	σ (μm/yr)
v_{g1}	1.8	1.2	2.4	1.7
v_{g2}	0.8	0.5	1.7	1.1
v_s	11.5	9.4	12	7.2

[1]μ is the mean, and σ is the standard deviation

A criterion that establishes an acceptable value for p_f with respect to the rupture limit state is considered. Computations are performed to assess the probability that the limit state equation will not be satisfied. This analysis uses the load and resistance factors specified for design of MSE retaining walls in the current edition of the AASHTO LRFD Bridge Design Specifications (AASHTO, 2012) and described by Berg et al. (2009). Table 2 is a summary of the resistance factors for the tensile resistance of metallic reinforcements as presented in the current AASHTO specifications. The analysis considers static loading and a load factor that is compatible with static earth load calculations ($\gamma_{P\text{-}EV}$ = 1.35). Other required input includes the load bias statistics, which are available from the literature and the same as those used for NCHRP Project 24-28 (Fishman and Withiam, 2011); and resistance bias statistics computed on the basis of the observed performance of metal reinforcements.

The limit state equation is described as

$$g(R,Q) = R - Q > 0 \tag{1}$$

where R is the resistance and Q is equal to the tensile load carried by the reinforcement. The Monte Carlo simulation technique was used with Equation (1) to assess the probability of failure considering uncertainties with respect to yield strength, metal loss and remaining cross section as described by Fishman et al, (2010) and Fishman and Withiam (2011).

Table 2. Resistance Factors for Tensile Strength for MSE Walls with Metallic Reinforcement and Connectors from Table 11.5.6-1, AASHTO (2012)

Reinforcement Type and Loading Condition	Resistance Factor
Strip Reinforcements	
Static Loading	0.75
Combined Static/Earthquake Loading	1.00
Grid Reinforcements	
Static Loading	0.65
Combined Static/Earthquake Loading	0.85

Figures 1 and 2 are typical results from the reliability analysis that include a description of resistance bias (Figure 1) and the probability that Equation (1) will not be satisfied (Figure 2). The resistance bias is the ratio of the remaining strength based on observed metal loss to the remaining strength considering the nominal (nom) values of metal loss used in design ($\frac{T_{remaining}^{observed}}{T_{remaining}^{nom}}$). Nominal strengths are computed using the form of the AASHTO metal loss model but considering $\overline{V_s}$ = 12 μm/yr, 15 μm/yr, or 20 μm/yr. The AASHTO model also includes $\overline{V_{g1}}$ = 15 μm/yr and $\overline{V_{g2}}$ = 4 μm/yr where the capital letter and the overbar denote nominal values used in design and the subscripts are similar to those used in Table 1. Observations based on observed metal loss are computed using the statistics described in Table 1.

Figure 1 depicts the bias computed using a nominal value of $\overline{V_s}$ = 15 μm/yr and statistics and distribution of data corresponding to "good" fill. The mean bias is 1.74 with a standard deviation of 0.41 and a normal distribution (model) appears to be a good fit to the data.

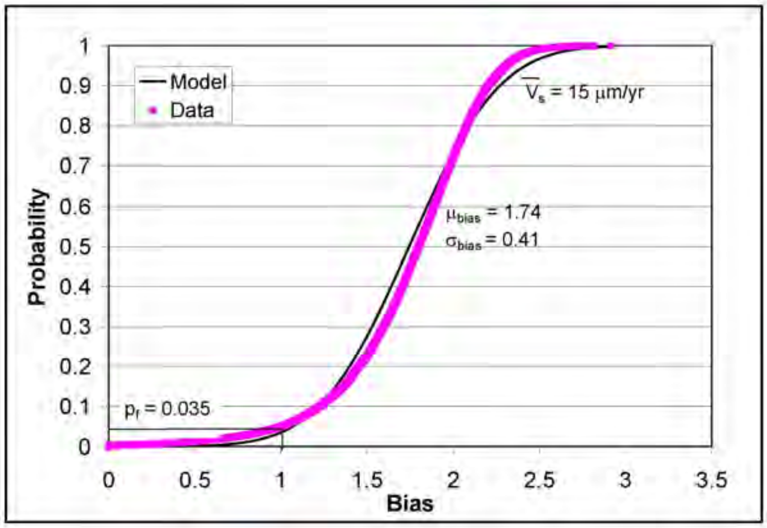

Figure 1. Computed Resistance Bias

Figure 2 depicts the probability that the limit state equation will not be satisfied. The results are plotted in terms of g(R, Q) along the abscissa and the standard normalized variable, Z, (number of standard deviations from the mean) along the ordinate. The reliability index, β, is the value of Z when g = 0, and β is related to p_f. Figure 2 shows that β is approximately –2.32 for a nominal value of $\overline{V_s}$ = 15 μm/yr. This value of β corresponds to $p_f \approx 0.01$.

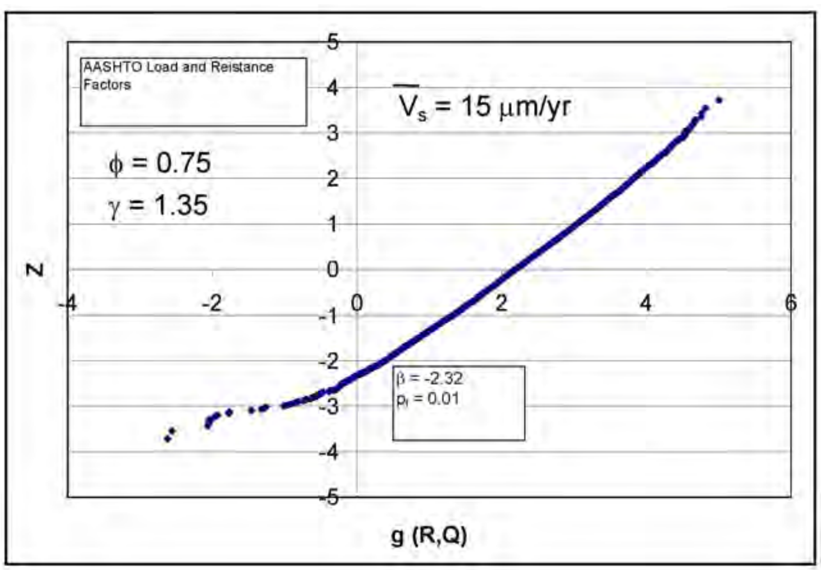

Figure 2. Computed Distribution for Probability of Failure

Table 3 is a summary of results obtained for different $\overline{V_s}$, and considering different sources of fill (good or high quality). The target reliability often used for design of highly redundant structures such as MSE walls is p_f = 0.01 (Allen et al., 2005). Thus, using $\overline{V_s}$ = 15 μm/yr with good quality fill is consistent with the reliability of other facilities and components for bridges designed using the current AASHTO standards. The reliability of MSE walls constructed with steel reinforcements and high quality fills exceeds $p_f = 0.01$ for all considered values of $\overline{V_s}$.

Table 3. p_f to g (R,Q) > 0

$\overline{V_s}$ $(\frac{\mu m}{yr})$	**HQ Fill**	**Good Fill**
12	0.004	0.015
15	< 0.004	0.01
20	<< 0.004	0.002

An alternate approach would be to use the same metal loss model regardless of fill type and adjust the resistance factors for LRFD considering the fill properties such that the same p_f is achieved via alternative sources of fill. As long as the metal loss model used in the analysis has the same form (e.g., linear model in terms of time), this approach renders the same results as altering the metal loss model (Fishman and Withiam, 2011).

DISCUSSION

Asset management decisions consider life cycle costs that include initial costs, and the costs of maintenance, rehabilitation, retrofit and replacement. Results from this study provide information that decision makers can use to evaluate relationships between these costs. Higher initial costs may be incurred via selection of higher quality fill or use of greater amounts of sacrificial steel. Higher initial costs lead to extended service lives and lower amortized costs for rehabilitation, retrofit or replacement. The costs of additional sacrificial steel and higher quality fill depend on the design of the wall (e.g., dimensions of wall, details of precast concrete facing and reinforcement connections, reinforcement type, etc.), the availability of fill sources and processing that may be necessary to produce the fill material. Alternatively, the agency may consider a higher p_f with respect to either the amount of sacrificial steel utilized in the design, or with respect to fill selection. The latter approach amounts to lower initial costs and corresponding higher costs for maintenance, rehabilitation, retrofit and replacement.

Performance monitoring as described by Elias et al. (2009) is also recommended to improve estimates for expected service lives. The analysis described in this paper relies on data obtained from sites distributed across the United States and Europe. These data include variances that have a significant effect on the corresponding calculations of $p_{f.}$ Variance can be reduced with local and site specific data that can be used to assess the condition of reinforcements over time and establish metal loss rates that correspond to local conditions and sources of fill. Thus, benefits from maintenance operations may be realized and improved estimates of service life may be obtained from monitoring such that costs for rehabilitation, retrofits, and replacements can be revised, and implementation scheduled as needed.

CONCLUSIONS

Asset management of transportation corridors that incorporate embankments, bridge approaches and bridge abutments supported with MSE retaining walls must consider factors affecting the service life of the reinforcements. The most important factors affecting the durability and expected service lives of metal reinforcements used in the construction of MSE include the character and electrochemical properties of the fill material, use of galvanized steel reinforcements and the amount of sacrificial steel incorporated into the design. The database compiled for NCHRP Project 24-28 is reviewed and used to generate statistical models that represent the performance of galvanized steel reinforcements used with alternative sources of fill. Corrosion rates observed from data partitioned with respect to fill properties are useful to compute the effect of material selection on service life.

The study includes:

1. Review of existing data describing the performance of metal reinforcements within fill types that may be characterized as good or high quality.
2. Statistical modeling of the observed performance.
3. Monte Carlo simulations to compute the probabilities that selected design conditions, or design limit states, will not be met (i.e. quantify the reliability of service life modelling and MSE wall design)
4. Selection of a desired level of reliability and corresponding metal loss model parameters to provide for the use of alternative sources of fill.

The approach and the results described in this paper can be used for management of transportation assets. The paper addresses decisions about selection of materials including specification of fill alternatives and sacrificial steel, and how these decisions may affect future costs in terms of maintenance, rehabilitation, retrofit or replacement of aging infrastructure. Reliability analyses are described using an existing database. However, site specific monitoring to observe the performance of locally available sources of fill is recommended to reduce variance and corresponding uncertainty with respected to calculation of expected service life.

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