Title: **Corrosion in an Arid Environment and Condition Assessment of a 20-Year Old MSEW**

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Corrosion in an Arid Environment and Condition Assessment of a 20-Year Old MSEW

By K. L. Fishman, J. M. Salazar and H. K. Hilfiker

Abstract. Advanced corrosion was observed for three metallically stabilized earth (MSE) walls that were constructed in 1985 in Las Vegas, Nevada. The wall backfill was reinforced with plain steel welded wire fabric (WWF) manufactured from cold-drawn wire. Data presented in this paper suggest that elevated levels of corrosion may be attributed to the aggressiveness of the backfill used on this project, which had characteristics typical of soil and aggregates native to an arid environment. Metal loss and corrosion rate were observed from measurements made on samples exhumed from test pits, and from linear polarization resistance (LPR) measurements on in-service reinforcements. If the aggressiveness of the backfill is recognized, the observed corrosion rate is predictable and consistent with estimates of metal loss from mathematical models of service life, and observations available in the literature describing the performance of plain steel reinforcements at other sites. A reasonable comparison between direct physical observation and corrosion monitoring with nondestructive testing (LPR) was observed. This further demonstrates that nondestructive testing with LPR provides a means to evaluate the condition of MSE walls and observe elevated levels of corrosion.

INTRODUCTION

In 1985, three metallically stabilized earth (MSE) retaining walls were constructed in Las Vegas, Nevada supporting the bridge approach, on ramp and highway embankment near the intersection of Interstate 515 (I-515) and Flamingo Road. In 2004, as part of a highway improvement program, the Nevada Department of Transportation (NDOT) began constructing sound walls along the edge of the I-515. One of the sound walls was a twelve feet tall, integrated slab/sound wall, founded on MSE fill just north of the Flamingo Road/I-515 intersection. A shallow excavation for this sound wall foundation exposed reinforcements near the top of the existing MSE wall, and corrosion was observed. The NDOT was concerned about the remaining service-life of the reinforcements, and the need to demonstrate a service life of 75 years for the new sound wall and MSE wall system. Based on these concerns, the NDOT decided to assess the condition of the reinforcements and implemented corrosion monitoring at the site.

Condition assessment and corrosion monitoring follow the techniques and practices recommended by Elias (1990, 1997) and Berkovitz and Healey (1997). This paper describes details of the MSE wall, site conditions including backfill characteristics, results from condition assessment and corrosion monitoring, and conclusions regarding the service-life of reinforcements.

MSE WALL DETAILS

Figure 1 illustrates the wall system, supplied by Hilfiker Retaining Walls (Hilfiker), which incorporates welded wire fabric as soil reinforcement. Hilfiker used cold drawn steel wire (ASTM A 82) to fabricate the welded wire fabric, which was not galvanized for this particular project. A typical reinforcement is 4 feet ten-inches wide and includes ten longitudinal wires. The longitudinal wires are tied together with transverse wires spaced approximately 2 feet center to center to create a bar mat. Each of the transverse and longitudinal wire intersections is spot welded, and a plate including steel pin connectors is welded to the proximal end of each grid for attachment to the wall facing units. Longitudinal wire sizes vary from W7 to W14, and transverse wires are either W7 or W9.5.

Typical precast concrete wall panels are 12.5 feet long and 2 feet high, and each unit contains two column sections. Panels are stacked during construction and are separated by an approximate ½ inch gap. Widened sections along the top and bottom portion of the panels facilitate attachment of soil reinforcements. Plans call for a nonwoven geotextile to cover the vertical panel joints, but a slit film, woven geotextile was observed in the field. We speculate that the slit film geotextile may have become clogged contributing to a lack of drainage and retention of moisture within the backfill. Grids are spaced behind the wall facing such that a grid spans across each panel joint, with one grid in the center of the panel separated by an approximately seventeen inch gap.

Three MSE walls are identified in Figures 2 (a) and (b) including Walls #1 and #2 along the Northbound Flamingo Road on-ramp, and Wall #3, which supports the highway embankment along the east side of the I-515, north of Wall #1. Wall #1 supports the approach to the I-515 viaduct crossing Flamingo Road. Wall #2 is beneath Wall #1 and supports the northbound on-ramp from Flamingo Road. Although the height of Wall #3 is less than twelve feet, the wall supports a sloping backfill that extends twenty to thirty feet above the top of the wall facing to the crest of the embankment. Wall #1 is the largest of the three at 800 feet long with a maximum height of 32 feet and soil reinforcement lengths that vary from 11 feet to 23 feet.

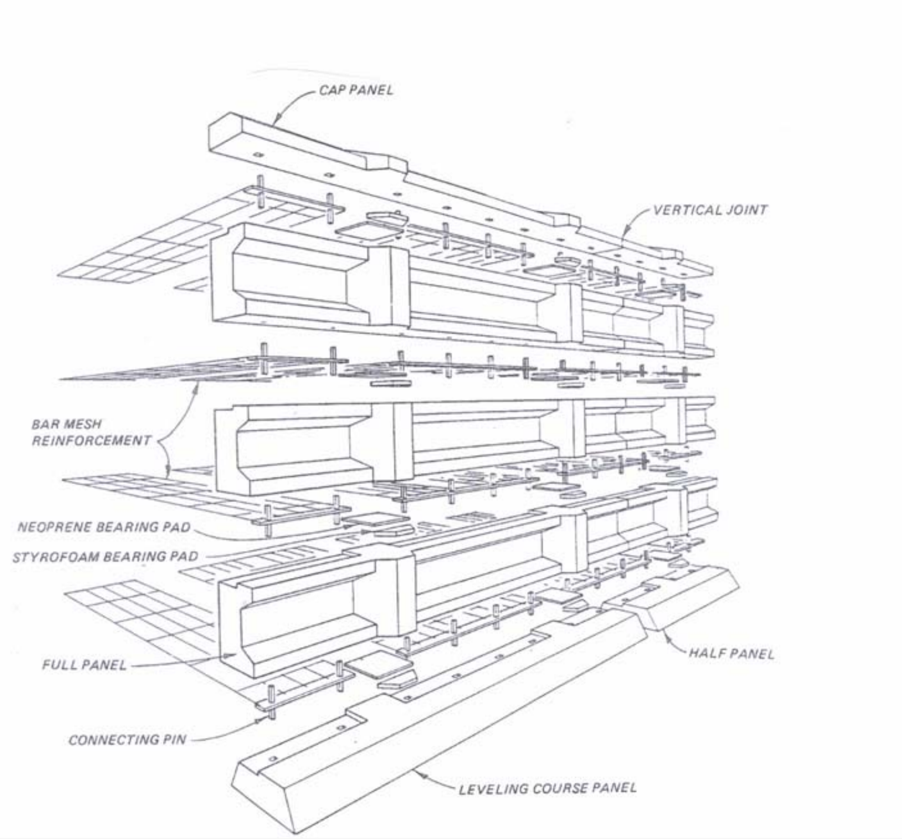

FIGURE 1. Schematic of MSE Wall System at I-515/Flamingo Rd. (after Hilfiker Company).

SITE CONDITIONS

The area behind the crest of Wall #1 is relatively flat and includes the pavement for I-515. The pavement structure sits atop the MSE backfill and includes a 10-inch thick Portland Cement Concrete (PCC) surface, and a 10-inch thick processed aggregate base coarse. An approximately 10 to 30 inch thick embankment cap, described as clayey sand with gravel, is found beneath the pavement structure. Beneath the cap is the MSE backfill, which is well-graded silty, sand with fine gravel. Based on information obtained from test pits and test borings advanced behind the wall, the cap and MSE backfill were slightly moist to moist and generally medium dense to dense in consistency. Below the top layer, reinforcements are placed within the MSE backfill, but possibly the top layer is located within the embankment cap. The MSE backfill is characteristic of screened aggregate derived from Las Vegas Valley concrete and aggregate sources, whereas the cap and embankment material are characteristic of natural soils encountered in the Las Vegas Valley (Terracon, 2004).

Similar MSE backfill conditions were encountered in the test pits advanced behind Walls #2 and #3. These walls retain the sloped highway embankment, covered with an approximately six-inch thick concrete slope paving. The pavement structure is located behind the embankment slope and beyond the limits of the MSE backfill at many locations.

Drainage for the pavement structure includes a number of drainage inlets located behind the retaining wall. A reinforced concrete drainage pipe (RCP) runs between the drainage inlets along Wall #1. The depth of this drainage pipe ranges from approximately three to nine feet beneath the pavement surface and within the MSEW backfill. A drainage inlet is also located behind Wall #2. These drainage facilities may have been a source of moisture within the backfill.

FIGURE 2(a). Wall # 1 Supporting Bridge Approach and Wall #2 Supporting On Ramp at I-515/Flamingo Rd.

FIGURE 2(b). Wall #3 Supporting I-515 Embankment North of Flamingo Rd. On Ramp.

Backfill Characteristics

Forty-three backfill samples were retrieved from test borings, test pits and openings advanced through the wall face at different elevations. Test data include grain size analysis, and measurements of moisture content, chloride and sulfate concentration, pH and resistivity. In general, the data suggest that the backfill is very aggressive relative to corrosion.

Figure 3 presents grain size distributions for the MSE backfill. Results from grain size analysis indicate that relatively coarser, more uniform, backfill is placed in proximity to the wall face. Samples retrieved further from the wall face appear to include a greater finer faction as indicated by the percent passing the No. 10 sieve. It appears that the backfill material ranges from a poorly graded sand in proximity to the wall face, becoming a poorly graded silty, sand at some distance behind the wall face. A possible scenario is that a uniform size backfill was placed near the wall face to minimize the required compaction effort. During construction, use of heavy compaction equipment near the wall face of a retaining wall must be avoided, so using uniformly graded, processed aggregate near the wall face is an attractive alternative. However, this practice can have an adverse effect on the vulnerability of the reinforcements to corrosion. The change in gradation and density, corresponding to differences in the porosity of the backfill, promotes development of macro cells due to differences in oxygen and moisture conditions. Development of these macro cells can promote corrosion of the reinforcements and the practice of placing more poorly graded backfill near the wall face should be avoided, particularly if salts are prevalent within the backfill.

The observed moisture content of the samples ranges from one to thirteen percent with a median of six percent. These measurements appear to have a random spatial variation. If we assume that the density or porosity of the backfill varies with respect to uniformity of gradation, these data suggest that the degree of saturation varies with respect to distance from the wall face. Assuming approximate densities of 100 pounds per cubic foot (pcf) and 120 pcf for material closer to, and further from, the wall face renders an estimated degree of saturation of approximately 25% and 40%, respectively. The possibility for the degree of saturation to vary over time in response to infiltration from storm events also exists. In the case of a porous (pervious to air) and noncohesive soil, soil induced corrosion increases with increasing water content, reaches its maximum at a water saturation of 30% to 50%, and thereafter decreases as the water content rises beyond 50% (Rehm, 1980). The estimated degree of saturation at the site ranges from 25% to 40% and therefore the moisture content is within the range of concern.

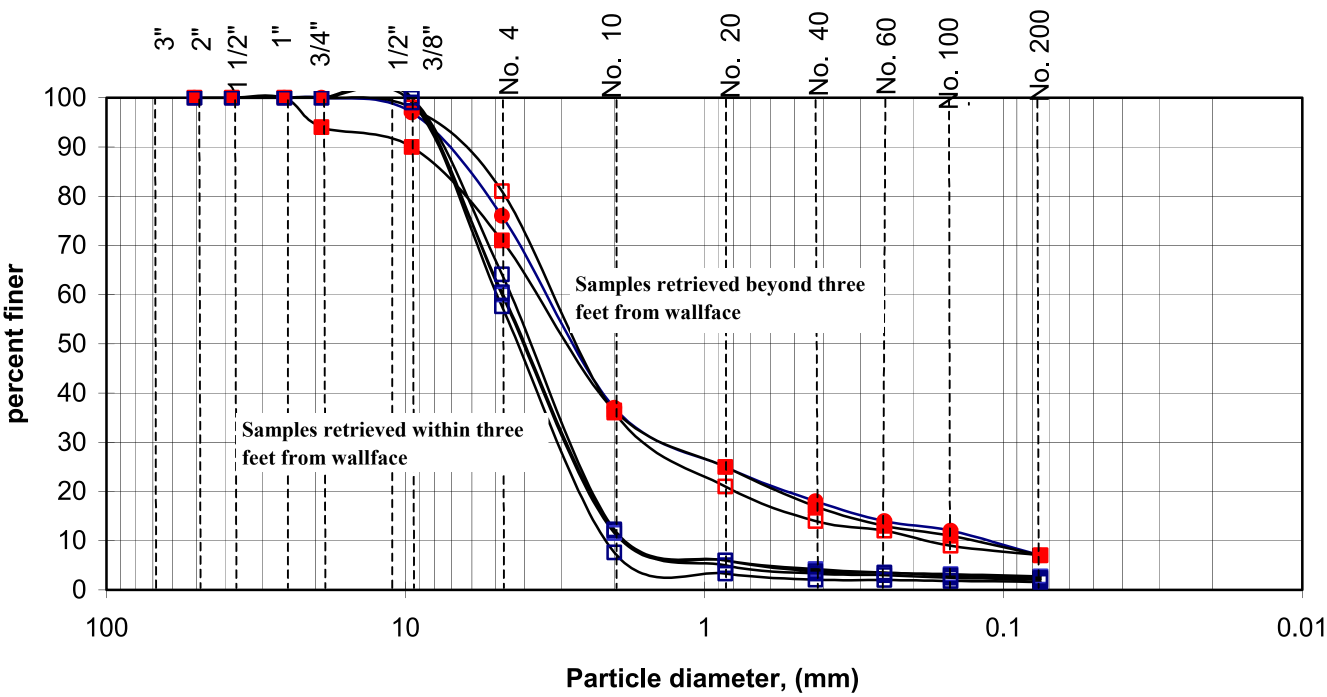

FIGURE 3. Grain Size Distribution for the MSE Backfill at I-515/Flamingo Road in Las Vegas, Nevada.

The measured electrochemical parameters including pH, resistivity, sulfates and chlorides also appear to have a random spatial variation. The measured pH indicates that the backfill is alkaline with a minimum, maximum and median measurement of 8, 10 and 9, respectively. Salt concentrations are observed in terms of chloride and sulfate ion concentrations. Chloride concentrations are slightly elevated at several locations (>50 ppm), and the measured sulfate concentrations range from less than 200 parts per million (ppm) to 9075 ppm with a median of 660 ppm. The median measured resistivity is approximately 1000 Ω-cm. Generally, soil resistivity is inversely proportional to salt concentration, and these measurements compare very well with published correlations between resistivity and sulfate concentration (USDA, 1969; Rehm, 1980).

Generally, ground conditions are considered aggressive if the resistivity of the backfill is less than 2000 Ω-cm and if sulfates and chlorides are present in sufficient quantities. Chloride concentrations above 50 ppm and sulfate concentrations higher than approximately 200 ppm to 500 ppm are cause for concern (Rehm, 1980). The following table provides general measures of corrosion potential based on the results of resistivity testing (NACE, 1985).

Corrosiveness of Soils (NACE, 1985)

Corrosiveness	Resistivity (Ω-cm)
Very Corrosive	0 to 1000
Corrosive	1000 to 2000
Mildly Corrosive	2000-10000
Progressively Less Corrosive/Noncorrosive	>10000

Based on the resistivity (1000 Ω-cm) and sulfate ion concentrations (700 ppm) measured on the samples, the backfill at the I-515/Flamingo Road site is considered very corrosive in terms of established measures of corrosion potential.

Reinforcement Condition

The conditions of reinforcements were observed from thirty-seven samples exhumed from eleven test pits distributed along Walls #1,2 and 3. Severe corrosion was observed along many of the exposed reinforcements as shown in Figures 4 (a) and (b). Corrosion was nonuniform, and metal loss appeared to be concentrated at distinct locations that were approximately an inch apart. In places, the wires were observed to have corroded to a pencil point, but nearby the wires appeared to be intact and often coated with precipitate. The deposit thickness was often up to an inch or more. These observations are consistent with macro cell corrosion.

Metallurgical testing and analysis were performed on specimens of steel and material adhered to the surface of the reinforcements. Results are obtained from chemical analysis including energy dispersive x-ray florescence spectroscopy (EDXRF) and x-ray diffraction; observation of the steel microstructure from the scanning electron microscope (SEM), and, mechanical testing including hardness and tension tests on selected wire samples. These results indicate that the relatively high rate of corrosion observed at the site is likely due to conditions within the backfill, and may not be attributed to any particular anomaly associated with the steel wire used to reinforce the backfill.

The precipitate appeared to be a combination of corrosion deposit and carbonate, or salts derived from the backfill. Three distinct colors of the deposits were observed including red (rust colored), whitish-tan and black. Black and red corrosion products were identified as magnetite (Fe_3O_4) and hematite or ferric oxide (Fe_2O_3), respectively. The, whitish, material adhered to the wires was identified as dolomite ($CaMg(CO_3)$). The dolomite is most likely the result of condensation of minerals present within the aggregate backfill. Another interesting result was the detection of significant concentrations of chlorine and sulfur within the red corrosion product (hematite).

No other anomalies or abnormalities were observed with respect to the steel composition, structure, hardness or tensile strength.

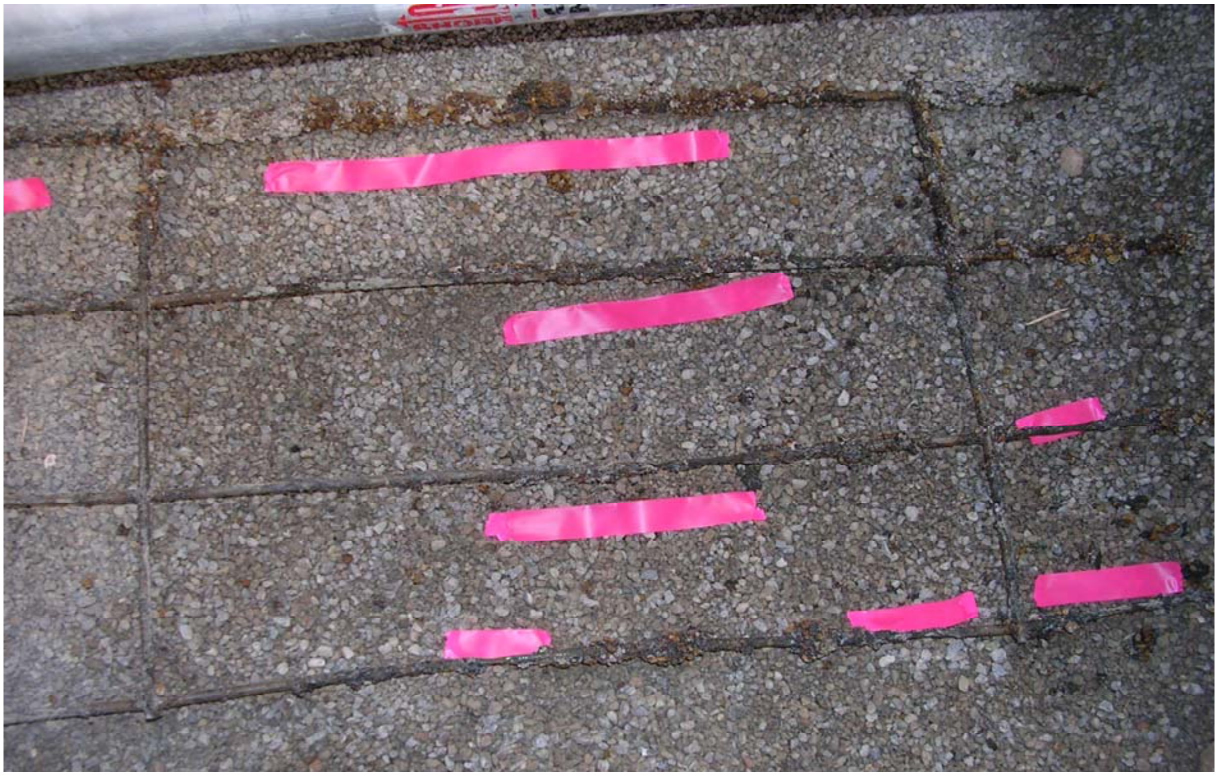

FIGURE 4(a). Reinforcement Observed in Test Pit.

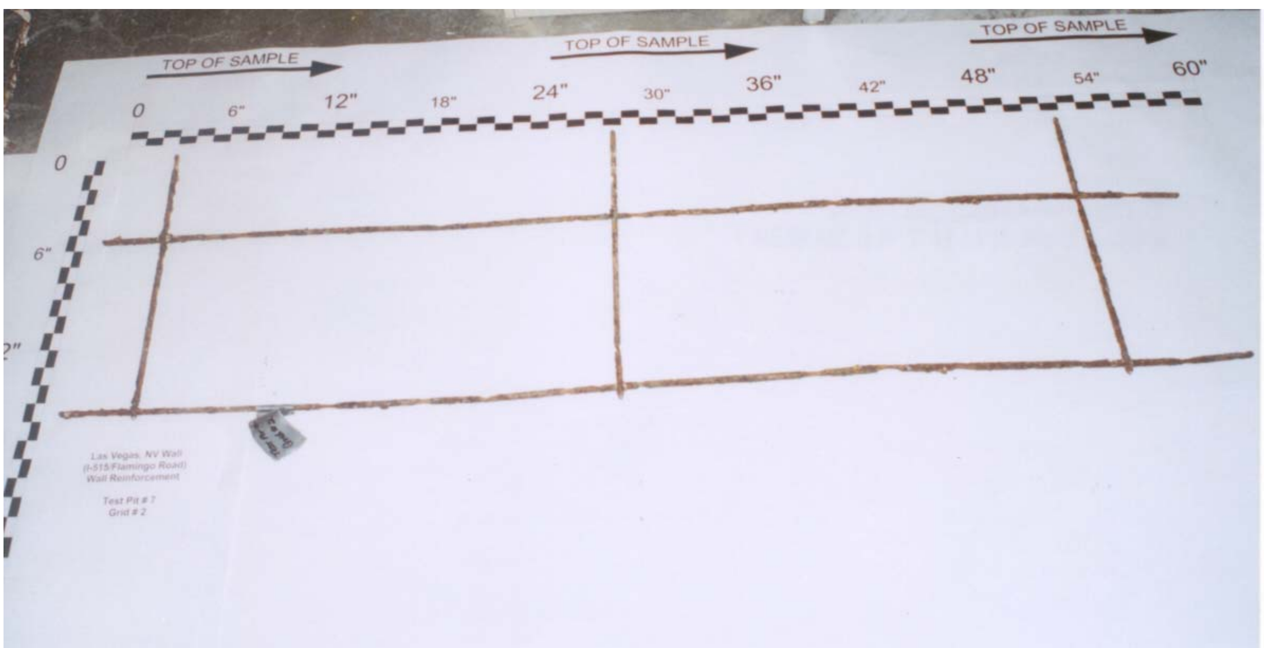

FIGURE 4 (b). Reinforcement Observed in Laboratory.

MEASUREMENT OF METAL LOSS AND CORROSION RATE

Metal loss measurements were made from direct physical observation of reinforcement samples, which were exhumed from test pits advanced within the MSE backfill. Alternatively, electrochemical tests, using the polarization resistance technique (LPR) as described by Lawson et al. (1993), Elias (1990, 1997) and Berkovitz and Healy (1997), were used to monitor corrosion rates (instantaneous). Forty-five reinforcements were wired for monitoring with the LPR technique, and twenty-seven steel and nine galvanized coupons were distributed within the backfill along Walls #1, #2 and #3. Direct physical measurements and electrochemical test techniques (LPR) each have inherent advantages and limitations, however, some of the limitations are overcome by performing both measurements; and by using the results to calibrate mathematical models of corrosion rate available in the literature.

Direct physical observations are useful to assess the nature of corrosion, loss of reinforcement capacity from corrosion, and the idealized uniform corrosion rate. Corrosion rate, as an average over the age of the structure, may be computed by dividing the metal loss by the age of the reinforcements. Data from direct physical measurement are also useful for comparison with measurements of corrosion rate from LPR. However, direct observations are limited because all of the reinforcement samples were exhumed from elevations within five feet from the top of the wall face.

The LPR technique is a nondestructive test, whereby reinforcements at elevations ranging from the top to the bottom of the wall are accessed through the wall face. Results from LPR are useful to obtain a better spatial distribution of corrosion rate measurements. The corrosion rate measured with the LPR technique is an average with respect to the surface area of the reinforcement sample. Therefore, the maximum rate of corrosion is not directly determined from the results of LPR. Also, a number of LPR measurements with respect to time must be made to assess the temporal variation in corrosion rate, and estimate metal loss.

Metal Loss

Metal loss was observed from thirty-seven exhumed reinforcement samples by measuring the remaining diameter at selected locations with a pair of calipers having a sensitivity of ±0.0005 inches. Corrosion deposits and precipitate were removed from the surface of the samples prior to making measurements. The metal loss study includes approximately twenty-eight hundred measurements of remaining diameter.

Two quantities are estimated based on the measurements of remaining diameter including:

1. remaining capacities of the exhumed reinforcements, and
2. “statistical” or “idealized” uniform metal loss.

Remaining Capacity

Reinforcement samples are approximately four feet wide, five feet long, sections of WWF and include approximately eight longitudinal and two transverse wires. Along each wire specimen a critical location is identified corresponding to the smallest remaining diameter observed at any point along the specimen. The maximum loss of section was most often observed at least three feet behind the wall face. This is consistent with the development of macro cells wherein corrosion would occur in the anodic area of the steel surface within the less porous, more oxygen deprived backfill.

The remaining diameters at each critical section for all the wires included within a corresponding reinforcement sample are averaged to render the average diameter remaining for the sample. The remaining reinforcement capacity is computed as the product of the average remaining wire diameter, the number of wires per reinforcement (10), and the allowable tensile stress ($0.48f_y$). According to ASTM A82, the specified minimum yield stress, f_y, of the cold drawn steel wire used to manufacture the reinforcements is 70 ksi.

The largest average remaining wire diameter for any of the thirty-seven reinforcement samples was 0.234 inches and the lowest was 0.06 inches. Grids observed from test pits excavated near pavement drainage facilities appear to have lost more capacity compared to grids observed in other locations. These data appear to be randomly distributed and symmetric with respect to the mean (μ) when the grids exhumed near drainage facilities are excluded. The mean remaining wire diameter observed at the critical locations is 0.183 inches, corresponding to an average allowable capacity of 8838 pounds/grid or 1413 pounds/ft considering a 58 inch wide grid and a coverage ratio of 0.773.

Uniform Metal Loss

Estimation of metal loss is in terms of the loss of thickness neutralized through corrosion, which is often expressed in terms of an "idealized" or "statistical" uniform metal loss. If we consider metal loss as uniformly distributed, we may compute a corresponding uniform remaining diameter for all the wires included in the sample. The concept is useful for interpretation of corrosion rate measurements and comparison to available mathematical models of uniform corrosion. In fact, because these losses in thickness are nonuniform, the ratio "relative loss of capacity/relative uniform loss of section" is higher than one (Jackura, 1987; Elias, 1990; Smith et al., 1996).

Measurements of the remaining diameter are made at close intervals along each wire to assess the uniform loss of cross section of a sample. The remaining uniform diameter is the integration of the measured diameters divided by the total length of the wires included in the sample. Uniform loss of thickness is computed as the initial radius minus the remaining uniform radius. Uniform rates of corrosion are estimated by dividing the uniform loss by the age of the samples (≈20 years). Computed uniform rates of corrosion range between 5.2 μm/yr and 29 μm/yr, with a mean of approximately 14 μm/yr.

LPR Measurements

The range, average, and distribution of corrosion rates measured for reinforcements using the LPR technique within Walls #1, #2 and #3 are similar. Corrosion rate measurements range from 0.75 μm/yr to 76 μm/yr. On average the corrosion rates observed in March (μ = 11.8 μm/yr, standard deviation (σ) = 13.9 μm/yr) were higher than those obtained in August (μ = 8.9 μm/yr, σ = 8.6μm/yr). LPR measurements correspond to a uniform corrosion rate at an instant in time. Thus, corrosion rates measured with the LPR technique compare reasonably well with direct observation of uniform metal loss.

In particular, significantly higher rates of corrosion were observed during March in the vicinity of drainage facilities located within the backfill behind Wall #1. Subsequent to the initial investigation and excavation of test pits, the area behind Wall #1 was capped with flowable fill in February 2004 and may have still been relatively moist in March of 2004. However, by August 2004 the backfill may have lost moisture, due to lack of recharge, increasing the transient resistivity of the backfill and affecting a lower corrosion rate. Higher corrosion rates were also observed behind Wall #2 in the vicinity of a drainage inlet (DI-4).

Free corrosion potential is also measured as part of the LPR measurement. Measurement of free corrosion potentials is useful to access the presence of corrosion and remaining zinc in the case of galvanized reinforcements (Elias, 1990; Lawson et al. 1993)). Observed free corrosion potentials appear to correlate well with respect to station along the wall face. Most of the reinforcement corrosion potentials are in the range associated with corroded steel surfaces. Free corrosion potentials for steel coupons are lower than those for reinforcements, and are expected to increase as coupons corrode over time. Also, the potentials of galvanized steel coupons are lower (more negative) than steel coupons installed at the same location. The potential of the zinc coupons will increase as the zinc is consumed. Future monitoring of galvanized and steel coupons will be useful for documenting the durability of zinc coating in this environment.

DATA ANALYSIS

Several models are available in the literature for computing metal loss and rate of corrosion applicable to MSE reinforcements. Constants for describing corrosion rate are based on electrochemical parameters measured for the MSE backfill such that corrosion rates and metal loss may be computed for normal, moderate and aggressive backfill environments. In 1984, CALTRANS implemented the following metal loss model in their Interim Design Criteria for considering durability of plain steel reinforcements (Jackura et al., 1987):

$$\mathbf{A = (D\text{-}2K(Y\text{-}C))^2/D^2 \times 100\%} \qquad (1)$$

where,

A = % of the original cross-sectional area remaining
D = Original diameter, (inches)
Y = Time of exposure, years
K= General Corrosion Rate factor (K=0.0028 for corrosive backfill, and 0.0011 for alkaline soils with R > 1000 Ω-cm)
C = Useful life of Coating, years (For Bare Steel, C=0).

Equation (1) accounts for localized corrosion and can be used to compare with the remaining capacity observed for reinforcements. According to the shop drawings, the wire size used at the I-515/ Flamingo Road site is W7, corresponding to an original diameter, D, of 0.298 inches. Calculations with Equation (1) predict that 40 percent of the original cross sectional area remains after 20 years of service at the site. Considering a mean remaining wire diameter at critical locations of 0.183 inches, the remaining capacity ($\mu = 38\% = (0.183)^2/(0.298)^2 \times 100\%$) observed from reinforcements exhumed at the I-515/Flamingo Road site compares very well with expectations based on use of Equation (1). If backfill conditions at the I-515/Flamingo Road site are assumed to be nonaggressive, Equation (1) predicts that approximately 73 percent of the original cross section would remain after twenty years of service, and the remaining cross section would not degrade to 40 percent of the original until reaching a service life of fifty years.

Corrosion rate measured with the LPR technique may also be compared with expectations based on an "idealized" uniform loss of cross section. This comparison must also consider that the LPR measurements provide an instantaneous measure of the corrosion rate. The possibility that corrosion rates were higher at an earlier point in time may be considered with an appropriate mathematical model for uniform corrosion rate.

Based on the work of Romanoff (1957), the following uniform corrosion rate model is proposed for steel reinforcements in aggressive ground conditions (Elias, 1997):

$$\mathbf{X = 40t^{0.8}} \quad (2)$$

and,

$$\mathbf{r = 0.8\ (40)\ t^{(-0.2)}} \quad (3)$$

where,

X = metal loss, i.e. loss of radius (μm),
t= time (years), and
r = corrosion rate (μm/year)

Equation (3) renders a corrosion rate of 17 μm/year at t= 20 years. This compares reasonably well with the average corrosion rate measured with the LPR technique (12 μm/year). Thus, it appears that LPR measurements are consistent with direct physical observations at the I-515/Flamingo Road site, and expectations based on corrosion rate models applicable to aggressive backfill conditions. This demonstrates that, if interpreted properly, and with knowledge of age and type of reinforcements, corrosion rate measurements with the LPR technique may be used to identify unusually high rates of corrosion at a site. These interpretations should still be verified with direct physical observations on exhumed reinforcements. However, fewer destructive samples are needed if they are supplemented with NDT results from LPR measurements.

Using Equation (2), the expected uniform metal loss for reinforcements at the site is 0.017 inches (439 μm) after 20 years of service. In comparison, the average loss of thickness at critical locations is 0.058 inches ((0.298-0.183)/2 = 0.058 inches). Considering the mean of the uniform corrosion rate measurements obtained with LPR measurements is approximately 70% of that obtained from Equation (3), the ratio between the observed average of the maximum loss of wire thickness, and the uniform loss of thickness is between 3 and 5. This ratio is useful to estimate remaining capacity of plain steel WWF reinforcements in these backfill conditions using the LPR technique. Thus, the NDOT may utilize NDT to evaluate similar walls in the Las Vegas area.

SUMMARY AND CONCLUSIONS

Summary

1. Based on results from laboratory testing of forty-three samples, the backfill at the site is considered to be very corrosive. Metallurgy tests conducted on samples of exhumed reinforcements reveal that the relatively high rate of corrosion observed at the site is likely due to conditions within the backfill, and may not be attributed to any particular anomaly associated with the reinforcements. The maximum metal loss observed along reinforcements exhumed from the test pits occurred at locations at least three feet behind the wall face. This

observation is consistent with development of macro cells between the front and rear portions of the reinforcements; possibly due to variation in the porosity of backfill.

2. Direct observations of metal loss were made from thirty-seven samples of corroded reinforcements exhumed from eleven test pits. These data are useful to assess the nature of corrosion, loss of reinforcement capacity from corrosion, and the idealized uniform corrosion rate. All of the reinforcement samples were exhumed from elevations within five feet from the top of the wall face. The LPR technique was used to monitor corrosion for reinforcements located at other elevations.
3. The LPR technique was used to monitor idealized uniform corrosion rate for forty-five reinforcements distributed along Walls #1, #2 and #3. Thirty-six coupons were also installed and monitored to serve as a basis for comparison. These data are useful to: (a) assess the spatial distribution of corrosion severity, and (b) further assess backfill conditions, and serve as a guide for selecting appropriate parameters for corrosion rate models and estimating remaining service-life.
4. LPR measurements indicate that corrosion is similar between Walls #1, #2 and #3 and similar corrosion rates are observed with respect to the top and bottom of the walls. Higher corrosion rates were observed in proximity to drainage structures placed within the backfill. Observations of reinforcement samples exhumed from test pits also indicate that Walls #1, #2 and #3 are in similar condition.
5. The LPR technique measures uniform corrosion rate at an instant in time and does not render maximum loss of section, or directly provide an estimate of remaining service life. Results may be used to select or calibrate appropriate corrosion rate models for estimating existing condition and projecting loss of section. Estimated rates for idealized uniform corrosion are consistent between direct observations of exhumed reinforcements, LPR measurements, and equations available in the literature. Based on these estimates, the average uniform loss of thickness (wire radius) after twenty years of service ranges from 0.010 inches to 0.017 inches, corresponding to a uniform corrosion rate of 0.0005 in/yr to 0.0008 in/yr (12 μm/yr to 20 μm/yr).
6. The average of the maximum metal losses observed at critical locations along the exhumed reinforcement samples corresponds to loss of thickness equal to 0.0575 inches. The maximum metal loss relates to the remaining grid capacity, which on average is approximately 38 percent of the original grid capacity (i.e. on average the reinforcements have lost 62% of their capacity from corrosion). This is consistent with design equations available in the literature for estimating the necessary thickness of sacrificial steel for reinforcements within a corrosive backfill environment.
7. The ratio between idealized uniform loss of thickness and the average of the maximum loss of thickness observed from these data ranges from 3 to 5. This is consistent with the statistical correlation for round bar elements cited in the literature (Romanoff, 1957; Jackura et al., 1987; Smith et al., 1996).

Conclusions

The highest remaining capacity observed from any of the reinforcement samples retrieved at the site is 63%, and on average the remaining capacity is 38% of the estimated original capacity of the reinforcements. Calculations of tension in the reinforcements for the MSE walls indicate that at some locations the computed reinforcement tension exceeds the allowable when metal loss from corrosion is considered. Essentially, the reinforcements are now in the condition anticipated at the end of 50 years, i.e. approximately two and a half times the anticipated corrosion rate (assuming that in 1984 the design objective was 50 years).

All three walls at the site appear to have experienced elevated levels of corrosion. These elevated levels of corrosion may be attributed to the aggressiveness of the backfill utilized on this project, and the presence of moisture within the backfill. If the aggressiveness of the backfill is recognized, the observed rate of corrosion is predictable and consistent with estimates of metal loss from mathematical models of service-life, which are based on observations of the performance of plain steel reinforcements documented in the literature.

A reasonable comparison between direct physical observation of metal loss and NDT was observed. Results from NDT must be interpreted carefully in terms of the age of the reinforcements, the tendency for corrosion rate to attenuate with respect to time, and the relationship between idealized uniform corrosion and loss of reinforcement capacity. Nondestructive testing using the LPR technique provides a means to evaluate the condition of MSE walls and determine if elevated levels of corrosion have occurred, if details of the reinforcements, wall construction and age of the wall are known. Results from NDT must be verified with direct physical observations, albeit less than would be necessary in the absence of NDT.

ACKNOWLEDGEMENTS

Barry Berkovitz, P.E. from the FHWA conducted a preliminary evaluation of the site and recommended that NDOT conduct corrosion monitoring and consider alternatives to retrofit and remediation of existing walls. McMahon & Mann Consulting Engineers, P.C. conducted the condition assessment and corrosion monitoring under contract with the NDOT (Agreement #P068-04-020). Mr. Parviz Noori, P.E., from NDOT, administered the contract and provided technical oversight during the course of the study. Wayne Kinzer, NDOT resident engineer, facilitated access to the site and provided services in support of field activities. Hilfiker Retaining Walls provided coupons for corrosion monitoring and the FHWA loaned their PR Monitor for making LPR measurements. NDOT, Terracon, Inc. and Geotechnics, Inc. performed laboratory testing on backfill samples, and Adirondack Environmental Services, Inc. performed metallurgical and chemical analysis of corroded reinforcement samples. Las Vegas Paving, Inc. and Capriatti Construction Inc. provided field services including access to backfill through the wall face and advancing test pits at the site.

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