Reduced Zinc Loss Rate for Design of MSE Structures

A White Paper and
Proposal to Change the Metal Loss Model
in the
AASHTO Specifications for Design of MSE Walls

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A White Paper by the Association for Metallically Stabilized Earth

ABSTRACT

Mechanically Stabilized Earth (MSE) structures using galvanized steel reinforcements have been constructed in the United States since 1971; many have been in continuous service for more than 30 years. During design, reinforcement metal loss for both the zinc and the steel are calculated and sufficient sacrificial steel is added to the reinforcement section to assure an allowable stress condition at the end of the design life. Extensive laboratory and in-service structure investigations have confirmed both the validity and the conservatism of the design approach and of the metal loss model.

The American Association of State Highway and Transportation Officials (AASHTO) specifications for MSE walls (both Standard and LRFD) define the properties of both the galvanized steel reinforcements and the MSE wall backfill soils. Although a few cases of poor performance have been documented, these occurrences are always correlated with a very aggressive environment (attributed to backfill or to site conditions) outside the AASHTO limits. Data presented in this White Paper demonstrates that, when AASHTO-prescribed design and construction practices are followed, the performance of metallic reinforcements exceeds current expectations. Therefore, the data also demonstrates that the current AASHTO metal loss model is unnecessarily conservative. Revision of the metal loss model is proposed.

The *AASHTO Strategic Plan for Bridge Engineering* (2005) presents a set of Grand Challenges to be met by the bridge engineering community. The proposed revision of the metal loss model contributes to meeting Grand Challenge 2, "Optimizing Structural Systems," and Grand Challenge 4, "Advancing the AASHTO Specifications." The proposed revision of the metal loss model should be adopted not only for its technical correctness, but also for its contribution to meeting AASHTO's Grand Challenges.

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INTRODUCTION

Purpose of Paper and Connection to AASHTO *Strategic Plan for Bridge Engineering*

The purpose of this White Paper is to propose the following well documented revision to the AASHTO specifications for Mechanically Stabilized Earth (MSE) walls: the rate at which zinc is consumed from galvanized steel MSE reinforcements should be changed from 4 μm/yr to 2 μm/yr.

The proposed zinc loss rate was documented and verified by a major university study completed more than 25 years ago but, when the original AASHTO specification for MSE walls was written several years later, *the zinc loss rate was arbitrarily changed to a value twice that recommended by the study*. This White Paper synthesizes and analyzes data from that study and from many other sources that overwhelmingly supports the proposal that the zinc loss rate be reduced from 4 μm/yr to 2 μm/yr. In fact, the preponderance of the in-service data demonstrates an actual loss rate below 1 μm/yr, making the proposed rate of 2 μm/yr clearly conservative. The current loss model is more than twice as conservative as is necessary or appropriate, justifying approval of the proposed change.

Revising the AASHTO specifications to incorporate the proposed zinc loss rate contributes to meeting two of the Grand Challenges set forth in the AASHTO *Strategic Plan for Bridge Engineering*. Those Grand Challenges, and the ways this specification change works to satisfy them, are discussed below:

- Grand Challenge 2, "Optimizing Structural Systems," challenges bridge engineers "To understand the advantages and limitations of traditional, newer and emerging materials in terms of safety, durability and economy; and to develop structural systems (optimized materials, details, components, structures and foundations) for bridges and highway structures that efficiently employ these … optimized materials to assure a safe, minimum 75-year service life requiring minimal maintenance." A specific activity mandated by this Challenge is "optimization of geotechnical and structural systems for safety, durability and cost based on optimized materials and systems." Revision of the AASHTO specification proposed in this White Paper clearly contributes to structurally optimized, minimal maintenance, cost-effective MSE walls and abutments by revising design requirements to reflect many years of in-service data, experience and knowledge.

- Grand Challenge 4, "Advancing the AASHTO Specifications" seeks "To understand the limit states required for safe, serviceable and economical bridges and highway structures, and to develop enhanced reliability-based provisions addressing these limit states in a manner relatively consistent with traditional design practice and effort." The proposed revision to the specifications derives from a more precise understanding of the traditional limit state for service life design of MSE reinforcements, allowing designers to develop safe, reliable, more economical designs.

Thirty Years of MSE Experience

In the United States, Mechanically Stabilized Earth (MSE) structures using galvanized steel reinforcements (Figure 1) have seen increasingly widespread use and, in some cases, continuous service, for 34 years. The prevailing design philosophy has been that a structure should be in an allowable state of stress at the end of its design life. The approach to *metal loss* has been to calculate the expected loss of both zinc and steel during the design life, then to add sufficient sacrificial steel ("sacrificial thickness") to the section to assure the end-of-design-life allowable stress condition. Extensive laboratory and field (in-service structure) investigations have confirmed the validity and conservatism of the loss model and the design life philosophy.

The American Association of State Highway and Transportation Officials has promulgated a specification for the design of MSE walls (AASHTO, 2002; 2004) that defines the characteristics of both the galvanized steel reinforcements and the backfill soils to be used in MSE wall construction. Although a few cases of poor performance have been documented, these occurrences are always correlated with a very aggressive environment attributed to backfill or to site conditions that do not conform to the current design specifications. Data presented in this White Paper demonstrates that, when good design and construction practices as prescribed by AASHTO are followed, the performance of metallic reinforcements exceeds current expectations. The data also demonstrates that the current AASHTO metal loss model is unnecessarily conservative and that the AASHTO specifications should be revised to reflect actual performance. To support this conclusion, this White Paper describes the performance of galvanized steel reinforcements documented from nearly 150 observations distributed among 75 different sites throughout the United States and Europe, and uses this data as a basis to evaluate the metal loss model in the current AASHTO specifications.

History of the Metal Loss Model

A metal loss model for galvanized steel reinforcements must take into account the relationship between backfill characteristics and aggressiveness, the effect of time, and the presence of the zinc coating. The work of Romanoff (1957) suggested that the rate of metal loss is greatest in the first few years of burial and then slows to a steady but significantly lower rate. Similar results were obtained during 19 years of carefully controlled laboratory box tests conducted by TAI (1990) on representative galvanized steel reinforcement materials buried in backfills typical of MSE wall construction. An unexpected result of the box tests was the observation that many samples experienced extremely low metal loss during the zinc-loss period. This finding was subsequently supported by examination of in-service walls in California, Virginia, Florida, North Carolina and other states, where many examples of less-than-predicted zinc loss (and, therefore, zero loss of the still-protected steel) were noted.

The main conclusion from Romanoff's work, from the TAI box tests, and from in-service examinations, is that the current model clearly overestimates zinc loss in MSE walls. Grand Challenge 4 of the AASHTO *Strategic Plan*, and good engineering practice, both require economy in addition to strength and stability. Given the high backfill quality required by the

AASHTO specifications, the metal loss model in those specifications is overly conservative in calling for a zinc loss rate of 4 μm/yr after the first two years of service. Therefore, the AASHTO metal loss model should be revised, based on 30+ years of experience and data, to give practicing engineers confidence they are designing the most economical and structurally efficient MSE structures possible.

Need for Revisions to the AASHTO Metal Loss Model

Details of the metal loss model adopted by AASHTO are discussed below. An important feature of the model is its recognition of a decrease in the rate of zinc loss after the first two years of service. In the early 1980s, it was generally accepted that, after two years of service, the rate of zinc loss could be conservatively taken as 2 μm/yr provided certain backfill criteria were met to assure a mildly to moderately aggressive environment. However, the higher zinc loss rate of 4 μm/yr was arbitrarily incorporated into the first (1992) edition of the AASHTO specifications for MSE walls and, in terms of the design life requirement for MSE structures, the current specifications are substantially unchanged from those adopted in 1992.

The AASHTO *Strategic Plan for Bridge Engineering*, adopted in its present form in 2005, mandates updating the specifications. The information and data presented in this White Paper will demonstrate that the existing specifications need to be updated in consideration of the observed performance of in-service facilities. Revisions to the existing specifications are proposed and supported with the necessary documentation and analysis of service life data.

TECHNICAL RESOURCES

Existing resources provide information on observation of metal loss and the useful service life of MSE reinforcements. Results from laboratory and field studies demonstrate the effects of backfill characteristics, climatic factors, and construction practice on durability and performance of MSE structures. Well documented case studies are also available describing condition assessment and metal loss measurement for in-service MSE structures. Data sources cited in this White Paper are summarized below:

- <u>Romanoff Report</u>. Romanoff's report, "Underground Corrosion" (NBS Circular 579, 1957, National Bureau of Standards [now named National Institute of Standards and Technology]), is the seminal and most comprehensive reference on underground metal loss. Comprehensive as it was, less than 10 percent of the data from this 47-year study came from granular soils such as those used in MSE walls, and even less of the data came from galvanized steel. The Romanoff report did, however, set forth the basic mechanisms of in-soil metal loss that form the basis of today's MSE service life computations.

- TAI MSE-specific studies. Systematic studies by the parent of The Reinforced Earth Company (RECO), Terre Armee Internationale (TAI), in conjunction with the Laboratoire Central des Ponts et Chaussées (LCPC, the French Central Laboratory for Bridges and Roads), developed a defining body of knowledge regarding the metal loss behavior of galvanized mild steel in granular soil (Darbin et al, 1988). The aim of this 20-year effort was to better understand the phenomenon of metal loss in the ground, to evaluate that behavior in terms of soils used in civil engineering work, and to identify the soil parameters that determine the kinetics of the metal loss process. Understanding those parameters allows the specifying of backfill soils within which the rate of metal loss will be both predictable and low.

- University of Stuttgart (Germany) Study. As described by Elias (1990), an analysis of NBS data by Stuttgart University (Rehm, 1980) focused mainly on data obtained from sites having soil characteristics similar to the engineered fills specified for construction of MSE walls. By considering the rate of metal loss to be constant over specific time intervals, the resulting Stuttgart model approximates the metal loss for both galvanized and carbon steel by linear extrapolation of observations. This study forms the basis for the bilinear metal loss model in the current AASHTO specifications.

- State Programs/Investigations. Thousands of MSE structures, reinforced with galvanized steel earth reinforcements, have been in service in the United States for more than 20 years. Various state programs and investigations into metal loss of in-service reinforcements are summarized below.

    1. California. Jackura et al (1987) presents the results of a survey of galvanized and plain steel elements used as soil reinforcement in mechanically stabilized embankment applications. Fourteen walls, utilizing five wall systems, were examined. Recommendations from this study include (1) use of galvanized steel reinforcements, and (2) coupons should be included as a contract item with all MSE wall construction contracts administered by CALTRANS to facilitate future monitoring of metal loss.

    2. Florida. The condition of the galvanized reinforcement in Florida DOT MSE walls was observed at selected sites (Rossi, 1996; Sagues, et al, 1998; Sagues, et al, 1999). Ten MSE walls were instrumented at eight different Florida sites for measurements of soil resistivity, electrical potential and metal loss rates. The reinforcement in the structures investigated was typically in good condition and the observed loss of metal from the galvanized elements was low. A deterioration model for service life forecasting was formulated using the field survey input.

3. Georgia. GDOT undertook a detailed metal loss evaluation effort in 1990 (Deaver, 1992). Walls to be included in the detailed evaluation were selected from among a comprehensive listing of 516 walls distributed throughout the state at 72 different projects. A preliminary screening exercise was followed by a more detailed review of selected walls with specific criteria for inspection including confirmation by site visits. Selection criteria included age, location (deicing salts used in Northern regions, sand backfills popular in the south), functional class (higher class likely to be deiced more often), wall design, backfill type (limestone, local sands), and suspect environment (e.g., saline or otherwise aggressive water at site). Six walls, located in the Atlanta area, were selected for detailed evaluation.

4. New York. NYSDOT began its *Mechanically Stabilized Earth Structures (MSES) Corrosion Evaluation Program* in 1998. Two hundred eighty three MSE walls, incorporated within 105 projects distributed throughout the state, are included in the NYSDOT inventory. This inventory is noteworthy because it includes some of the oldest MSE walls in the United States (25+ years). The NYSDOT MSE wall assessment program is a two-phase program. Information is collected during Phase I from the existing inventory relative to the electrochemical properties of the backfill. Then during Phase II, suspect walls are investigated for accelerated metal loss, and to monitor some walls not at risk to serve as a baseline. Four walls have been prepared for Phase II monitoring including installation of zinc, steel and galvanized coupons, and electrochemical monitoring activities (Wheeler, 1999, 2000, 2001, 2002; CC Technologies, 2000).

5. North Carolina. In early 1999, the North Carolina DOT reported on 46 MSE walls that had been constructed during the preceding 20 years (Medford, 1999). Because a few walls had been built with somewhat aggressive backfill material, a statewide metal loss monitoring program was initiated in cooperation with FHWA. This monitoring revealed no metal loss problems with any of the MSE walls.

6. Virginia. A structure in Virginia was thoroughly investigated in 1999 during its demolition (Anderson and Sankey, 2002). Samples of the galvanized reinforcements and of the surrounding backfill were retrieved and measurements were taken of the remaining zinc thickness and of the electrochemical properties of the backfill. Both the zinc thickness and the backfill properties were within industry standards. The zinc thickness remaining on the reinforcements was subtracted from the original zinc thickness, and the resulting loss of zinc was compared to the loss predicted by the linear loss model used to estimate the service life. After 20 years in service, the loss of zinc was only 40 μm, i.e. more than half of the zinc coating remained, and it was covered with approximately 40 μm of zinc

oxide. The zinc coating was performing better than the loss model predicted and no loss of the base metal had occurred.

7. Kentucky. The University of Kentucky, in conjunction with the Kentucky Transportation Cabinet, reported in 2005 on a database of more than 120 MSE walls, four of which were instrumented for evaluation of metal loss (Beckham et al, 2005). The walls were selected, in part, due to the use of backfills considered to be aggressive, but the "…data obtained indicate the designed sacrificial thickness will not be used during the design life of the structures." In addition, "No visible corrosion was observed in reinforcing elements removed from a mechanically stabilized earth wall that had been in service for more than 20 years."

- Industry studies. The Reinforced Earth Company (RECO) and Hilfiker Retaining Walls (Hilfiker) have completed several site-specific performance studies. In these instances, existing MSE walls are demolished as part of reconstruction efforts, or evaluated to consider the possibility of revised service-lives. These projects provide an opportunity to study metal loss of reinforcements after 5 to 20 years of service. Examples of completed studies include:

    - Wyoming – Bridger–Coal site – Hilfiker
    - Redding CA – Mercy Medical Center – Hilfiker
    - Oleans, CA – bridge approach and abutment – Hilfiker
    - New York – Sprain Brook Parkway – RECO
    - Florida – Pensacola St. – RECO
    - Virginia – Route 66 – RECO
    - California – San Louis Obispo – RECO
    - Iowa – I-35 Polk County – RECO
    - Kentucky – Bluegrass Airport – RECO
    - Colorado – I-25/470 Interchange – RECO
    - Pennsylvania – Bailey Mine – RECO

- FHWA. The Federal Highway Administration spearheaded efforts to evaluate metal loss and assess the condition of reinforcements from MSE walls constructed in the United States. Frondistou-Yannis (1985) evaluated four of the earliest of these walls in an effort to document the extent of metal loss and identify needs for further research and evaluation. Elias (1990) described implementation of electrochemical test techniques for monitoring the metal loss rate in in-service reinforcements. Seven walls located at sites distributed throughout the United States are included in a field demonstration describing implementation of these techniques. Berkovitz and Healy (1997) summarize the on-going metal loss monitoring activities of six states, and describe recommendations for establishing a systematic, rational, metal loss evaluation and monitoring program using electrochemical measurements.

RESEARCH ON MSE METAL LOSS MECHANISM

The LCPC, in the original French research program, undertook the physiochemical reconnaissance on soils and contributed to establishing criteria for the selection of MSE fill material. The metal loss mechanism is electrochemical in nature, meaning both electrical flow and chemical reactions are necessary for this phenomenon to occur. It came as no surprise, therefore, when both LCPC's statistical evaluation of existing data (Romanoff and other) and the earliest TAI results showed that the key soil parameters affecting the performance of MSE reinforcements are moisture content, pH, resistivity, and chloride and sulfate content. However, the details of the loss mechanism itself had to be understood in order for an appropriate loss model to be developed. These results will be reviewed, as they have an impact on the existing practice and should be considered in proposing changes to the AASHTO specifications.

Surface Irregularity vs. Differential Aeration Mechanisms

Metal loss from objects (such as MSE reinforcements) buried in soil depends on the presence of an electrolyte, because electricity must flow from anodic areas, which lose atoms, to cathodic areas that collect them. Metal loss micro-cells can be formed by micro-irregularities in the metal surface, such as a variation in crystalline structure, the presence of an impurity, or even a trace amount of oxide. These micro-irregularities exhibit micro-differences in electrical potential, causing metal ions to leave the anode, flow through the electrolyte, and be deposited on the cathode. The circuit is completed by the electrons returning to the anode through the body of the metal.

Another mechanism is called differential aeration, in which a cell is formed between a grain or clump of soil touching the metal and a surrounding water droplet connecting that particle to the metal. The cell exists due to the difference in oxygen concentrations between the exterior portions of the droplet - in contact with air between the soil particles - and those portions of the droplet deep under the soil grain and relatively “distant” from oxygen contact. The anode develops under the particle, where the oxygen content is least, while the cathodic area is under the water droplet.

Metal loss by galvanic action may also occur due to differences in oxygen and moisture contents along, or between reinforcements; or between reinforcements and the wall face. Macro-cells may exist due to the different level of backfill compaction at the wall face compared to other locations along reinforcements. Looser material near the wall face is more porous and is relatively more aerated compared to other locations. Thus, the oxygen-rich environment near the wall face is cathodic, and relatively oxygen-deprived areas, further away from the face, are anodic.

The potential also exists for macro-cells to develop between the soil reinforcement connection devices and the precast facing’s reinforcing steel, both of which are embedded in the concrete facing units. This effect is due to the difference between the pH of the concrete (highly alkaline) and that of the backfill (relatively neutral). Reinforcing steel in the concrete is passivated (see discussion below) by the alkaline environment and, therefore, is at a higher potential compared to the soil reinforcements. If macro-cells could develop, reinforcement connections would be anodic and the concrete reinforcing steel would be cathodic. However, the development of macro-cells is mitigated in practice by keeping the soil reinforcement connections electrically isolated from the concrete reinforcing steel embedded in the precast facing units.

Passivity

Passivity refers to the loss of chemical reactivity experienced by certain metals and alloys under particular environmental conditions. During passivation a surface film or protective barrier is formed that is stable over a considerable range of oxidizing power. Steel and zinc become nearly inert, and metal loss occurs very slowly after these metals are passivated. Forms of iron and zinc oxides, byproducts of the metal loss process, adhere to the reinforcement surface and remain in place as part of the protective film. These oxides also permeate the immediately-adjacent soil, enlarging the zone of protection around the reinforcement. Thus, a higher rate of metal loss is observed during the first few years of burial, during which time a protective (passivating) film of metal oxides is developing, along with its surrounding oxide-rich soil zone, followed by a much slower rate of metal loss subsequent to passivation of the base metal.

Metals that possess an active-passive transition become passive in mild to moderately aggressive environments. Zinc and steel will become passivated in backfill soils that meet the requirements specified by AASHTO, whereas reinforcements in highly acidic soils or in soils with high salt concentrations (i.e., soils not meeting the AASHTO requirements), may not become passivated at all. In addition, zinc will not become passivated in highly alkaline environments and, if the base metal is not passivated for any reason, loss rates over the life of the structure will be considerably higher than if passivation had occured.

Backfill Factors Affecting Metal Loss

Black (ungalvanized) steel loss in buried conditions is rapid below pH 4, occurs at a predictable, uniform rate in the pH range of 4.5 to 10, and diminishes linearly as pH exceeds 10. Galvanized steel loss occurs in two stages, however; first the outer layer of zinc, then the underlying steel. The loss of zinc is closely related to soil pH and resistivity. Zinc loss occurs most rapidly in highly acidic and highly alkaline environments (pH below 4.5 and above 11) with soil resistivity less than 1000 ohm-cm. MSE backfill soils are typically specified to be within the pH range 5 to 10 because this is also the stability range of the protective chemicals formed in the soil during the zinc loss process. In a study of granular soils structurally suitable for use as MSE backfills, over 90 percent had pH values between 6 and 8.5, and 99 percent had pH values between 5.5 and 9 (TAI, 1977).

Backfills high in organics (> 1%) are unsuitable for MSE structures due to the potential for microbial-induced metal loss. In such soils, sulfate reducing bacteria may create acidic conditions as a by-product of the consumption of organic material. This low-pH soil may lead to localized, pitting type metal loss.

Laboratory Test Results (Electrochemical Cells and Burial Boxes)

TAI studied metal loss from MSE reinforcements under carefully controlled conditions in the laboratory using small electrochemical cells and larger scale burial boxes (Darbin et al, 1988). The electrochemical cells were assembled using relatively small (compared to the burial boxes) plastic tubes containing specimens of reinforcements surrounded by soil. Electrodes were sealed into the ends of the tubes, serving as reference and counter electrodes, to facilitate measurements of metal loss activity at frequent intervals. Data obtained from such electrochemical cells are representative of very controlled conditions in terms of the electrochemical properties of the soils used in the experiment.

Tests with relatively larger burial boxes allow the burial of measured and weighed pieces of actual earth reinforcement, in soils similar or identical to those used in real structures, with moisture content adjusted to and maintained at natural, in-ground levels. Samples can be removed at prescribed intervals for cleaning, precise weighing and measurement of coating loss.

Electrochemical and burial box tests were begun by TAI in 1976 and continued for more than 20 years, yielding extensive data on MSE metal loss behavior. Most notably, for five representative soils (red schist, black schist, artificial sea sand, clayey sand and silty sand), long-term metal losses measured by the burial box tests were the same as, or less than, the losses measured in the electrochemical cells.

Advantages of Galvanization

Several advantages to the use of galvanized reinforcements have been documented, including:

- The zinc coating has a surface that is electrochemically more uniform than the surface of bare steel (Rossi, 1996). Thus, the presence of surface irregularities and their contribution to the loss process is minimized.

- For backfills that are considered mildly to moderately aggressive (i.e., meeting the requirement specified by AASHTO), the rate of zinc consumption is significantly less than that of steel (Romanoff, 1957; Darbin et al, 1988).

- Zinc becomes passivated in nonaggressive backfill soils and the zinc oxide formed during the metal loss process adheres to the reinforcement and binds with the soil near the interface with the metal surface (Rehm 1980; Darbin et al, 1988). The resulting passivation of the steel means the rate of metal loss for galvanized steel is less than that for steel that was never galvanized.

Metal Loss Model

Based on the electrochemical and burial box test data described in the previous section, Darbin described the loss of metal from galvanized steel by assigning specific values to the constant k in Romanoff's equation

$$P = kt^n$$

where

P = average thickness loss of metal (zinc + steel) for one side of the sample
k = coefficient depending on soil aggressiveness (k = 25 μm/year for soils with resistivity (R) ≥ 1000 ohm-cm and k = 20 μm/year for soils with R ≥ 3000 ohm-cm)
t = time
n = fractional exponent, typically 0.65.

This model is intended to determine average loss of thickness of the base metal, steel, at a service life of seventy-five years.

METAL LOSS MODELS, SACRIFICIAL THICKNESS, AND BACKFILL SPECIFICATIONS

AASHTO Metal Loss Model

The AASHTO metal-loss model defines the rates at which first zinc, then steel, will be lost from the MSE reinforcement section. As discussed in Comparison of Loss Models, below, the loss rate for steel in this model is *twice the average metal loss* (6 μm/yr, determined from weight loss). Therefore, the loss model is proportional to loss of tensile strength and no further adjustments are required. For *each exposed surface*, these rates are

Loss of zinc (first 2 years)	15 μm/yr
Loss of zinc (to depletion)	4 μm/yr
Loss of steel (after zinc depletion)	12 μm/yr

Using the specified 86 μm zinc thickness (ASTM A123, 2004), the expected life of the zinc is 16 years, followed by 59 years of steel loss of strength before the typical design life of 75 years is reached. At the end of the design life, the remaining steel section must be in an allowable stress condition for the maximum design load.

Sacrificial Thickness

Sacrificial thickness is the amount of steel that can be lost, or sacrificed, by the section while still maintaining a safe structure at the end of the design life. For the typical 75-year design life for MSE structures, using reinforcements galvanized with the specified minimum 86 μm of zinc, the AASHTO model requires 708 μm of sacrificial steel per side (1.416 mm total sacrificial thickness). The total structural section must be at least the sum of 1.416 mm sacrificial steel plus the steel required to carry the design load in an allowable stress condition.

Comparison of Loss Models

The exponential loss model (Darbin, 1988) and two bilinear loss models (AASHTO, 2002 and Stuttgart University [Rehm], 1980) are compared in Figure 2. The bilinear models show the rate of zinc consumption being greatest during the first 2 years, followed by a significantly reduced rate based on the passivation of zinc in backfill soils typical of MSE wall construction. Steel consumption begins after the zinc layer is consumed, at a rate reflecting passivation of the steel by the zinc oxide on the surface of the steel and in the surrounding soil.

Loss of MSE reinforcement thickness is calculated from weight loss measurements, using the implicit assumption that metal loss occurs uniformly over the entire surface of the reinforcement. In fact, metal loss occurs non-uniformly over a metal surface, with the cross section thickness in some areas less than in other areas. Since the region of least remaining section will control reinforcement tensile strength, the loss of tensile strength is taken as twice the tensile loss implied by the weight loss measurements (Darbin, 1988; Elias, 1990). This factor of two is conservative for galvanized steel (Darbin, 1988) and is shown on the right axis of Figure 2 (K = 2) and is already incorporated in the AASHTO and Stuttgart University models, as discussed previously. The Darbin model in Figure 2 shows a change of slope at the time of zinc depletion due to incorporating this factor of two in the loss of steel.

Backfill Specifications

The AASHTO metal loss model is considered valid when the backfill conforms to the following electrochemical limits:

- pH = 5 to 10
- Resistivity ≥ 3000 ohm-cm
- Chlorides ≤ 100 ppm
- Sulfates ≤ 200 ppm
- Organic content ≤ 1%.

Since these backfill materials are well understood and relatively available, there should be no change in the backfill specifications. As will be seen below, however, the specified backfill creates a significantly less aggressive environment than is assumed by the current AASHTO loss model, giving rise to the proposal in this White Paper to revise the loss model.

RECENT INVESTIGATIONS OF STRUCTURE PERFORMANCE

MSE Wall Database

The Association for Metallically Stabilized Earth (AMSE) has compiled a database documenting details of MSE walls constructed in the United States over the past 30+ years. This information is useful in describing the demographics and the attributes of the existing inventory and the evolution of the principles of good practice used in the construction of MSE walls throughout the United States. The data entry form used to solicit information about reinforcements, wall facing, wall geometries, and site and backfill conditions is shown in Appendix A. Appendix B presents charts summarizing the demographics of the inventory, while details of the inventory pertinent to metal loss, such as wall location, age and backfill electrochemical conditions are reported in Appendix C. Data were input into Microsoft Access™ to facilitate searching and querying of the information. The database is analyzed and attributes of the general population are compared to those walls for which performance and metal loss have been observed and documented.

The 780 walls that make up the database constitute a random sampling of the approximately 40,000 MSE walls constructed in the United States since 1972. Dates of construction range from 1973 through 1999, but well over half of the walls in the database were constructed between 1980 and 1985. Most of the walls are owned by DOTs and were, therefore, designed and constructed based on some form of the AASHTO specifications. Walls owned by the US Forest Service, other government agencies and private owners, however, may not have been built according to these, or similar, specifications.

The database includes 271 walls constructed with wire mesh or grid-type steel reinforcements and 509 constructed with steel strips. These walls are dispersed among 340 different projects (note that many projects in the database, especially DOT projects, include multiple walls). The majority of MSE walls constructed with grid reinforcement serve as retaining walls, but one third of the walls with strip reinforcements serve as part of a bridge structure (abutments or wing walls).

Charts in Appendix B reflect the geographic distribution of MSE wall construction. Six regions, as described by the Northeast Regional Climate Center at Cornell University (http://met-www.cit.cornell.edu), are used to distinguish climatic conditions on a regional scale. These regions are identified as Northeast, High Plains, Midwestern, Southeast, Southern, and Western.

Of the 780 walls in the inventory, the majority is located within the Western, Southern and Southeast regions, with almost half (370) located within the Western region alone. *(Note: The inventory is not intended to represent the distribution of all MSE walls but is probably representative of the population of these walls constructed before about 1990)* Therefore, a large percentage of walls in the inventory is located in an arid climate where backfill sources are alkaline, which describes the climate and soil conditions throughout a large portion of the Western region and parts of Texas (Southern Region). Compared to grid/wire mesh reinforcements, which are used predominantly within the Western region, use of strip reinforcements is more uniformly distributed. Approximately 40 percent of the walls constructed with strip reinforcements are located in the more temperate Southeastern and Southern climates, where soils are normally slightly acidic. Some of the walls located within these regions may also be located in a coastal environment.

Backfill data includes a total of 253 records from a total of 38 states. Fields of information include grain size distribution (181 records), Atterberg limits (35 records), resistivity (194 records), pH (190 records), chloride ion content (133 records) and sulfate ion content (130 records). The pH data are symmetric with respect to the mean of 7.2, and approximately 85 percent of the data are between pH 6 and 8.5. Resistivity data are skewed toward the higher side with a mean of 31,000 ohm-cm. Approximately 80 percent of the resistivity measurements are higher than 10,000 ohm-cm, and 50 percent are higher than 19,600 ohm-cm. These data are similar to data collected in France by TAI (1977), which indicated that approximately half of the walls included in the French survey had backfill resistivity higher than 10,000 ohm-cm and 96 percent had pH between 6 and 8.5.

The vast majority of the measured salt concentrations were low ($Cl < 100$ ppm, $SO_4 < 200$ ppm). Instances of low resistivity ($R < 3000$ ohm-cm for 12 out of 194 records) are always associated with high salt concentration; however, instances of high salt concentration are not always associated with low resistivity. A weak correlation between salt concentration and resistivity was observed, showing a trend similar to that reported by Rehm (1980) and Elias (1990).

Metal Loss Performance

Observations on MSE walls are used to document metal loss of in-service reinforcements. These observations are representative of construction practice in the United States over the past 30 years and are supplemented with data collected from European sites in the 1980s when these walls were between 10 and 20 years old. Observations consist of visual inspection, metallurgical analysis, thickness and weight loss measurements; and electrochemical measurements such as half-cell potential and linear polarization resistance (LPR).

Metal loss performance data is divided into two groups: walls for which good design and construction practices were followed and those where poor design and/or construction practices were followed. Good practice means backfill quality, construction practice and site details are in accordance with current specifications for design and construction of MSE walls (AASHTO, 2002). Poor practice is often associated with poor quality backfill, lack of proper detailing (e.g., poor drainage conditions), or poor control during construction leading to nonuniformities within the backfill. In all instances where poor performance has been observed, the performance is correlated with an aggressive environment attributed to poor quality backfill, poor construction practice or adverse site conditions.

Poor Practice

Performance observed from backfills not meeting the requirements of AASHTO (2002) is reviewed in this section. The data demonstrates the need to describe metal loss in terms of backfill quality and characteristics and emphasizes the importance of controlling backfill quality during MSE wall construction. Backfills that are clearly not suitable for MSE construction are distinguished from those that are suitable but correspond to relatively higher rates of metal loss, and from those for which superior performance and low rates of metal loss are anticipated.

As reported by Frondistou-Yannis (1985), a few early failures of reinforced walls in France and Spain have been attributed to accelerated metal losses. An MSE wall in Cap d'Agde, France, built in 1974, failed in a marine environment from rapid metal loss observed to be 17 times the design rate. The very poor performance was attributed to excess copper that crystallized in the aluminum alloy used for the reinforcing strips. Another incident in Nice, France, was attributed to the use of organic soil as backfill and to sulfate-reducing bacteria that caused accelerated loss of metal from the reinforcements. Failure of an MSE wall in Spain was due to a truck accident, which caused acidic chemicals to penetrate the wall.

Results from a comprehensive study of moderate to extremely high metal loss rates observed on MSE walls constructed, with one exception, in the United States, are described in this section. It is important to note, however, that none of these case studies represents MSE design and construction practice as it is *typically* practiced in the United States.
Poor performance, in terms of metal loss, has been documented for the 11 MSE walls listed in Table 1. Ten of the walls are located within the United States, and one is in South Africa. Nine of these case studies involve strip type reinforcements, while wire mesh reinforcement was used at two of the sites. With the exception of the walls in Brunswick, GA, and Las Vegas NV, all of the reinforcements were galvanized steel. Aluminum strip reinforcements were used at the Brunswick site, and black (ungalvanized) steel welded wire fabric was used in Las Vegas.

Table 1 includes a summary of backfill electrochemical properties, from results of laboratory tests performed on samples collected from each site. None of the backfills described in Table 1 meets the requirements specified by AASHTO. With one exception, all of the measured minimum resistivities are less than 1000 ohm-cm, and four of the sites have minimum resistivities less than 500 ohm-cm. This observation is in stark contrast to the backfill information included in the AMSE database, and from data collected at sites with good performance, where most of the measured minimum resistivities are greater than 10,000 ohm-cm. Backfills at the sites of poor performance also appear to be very high in salt concentrations, with some as high as 50 times the maximum allowed by AASHTO.

Table 2 summarizes the metal loss observed at each of the sites. Six of the measurements were physical measurements of loss of weight, thickness or tensile strength, and five were instantaneous metal loss rates measured with the LPR technique. Metal loss rate measurements are compared to those predicted by the AASHTO metal loss model and the known age of the reinforcements at the time of the measurement. Zinc was consumed in less than 16 years at four of the sites. These sites include performance data from South Africa, SUNY Ramps, I-85 Charlotte, NC, and Lovelock, NV. Three of these sites involve very aggressive backfills characterized by resistivities less than 700 ohm-cm, but the problems at the Lovelock, NV site were related to very high alkalinity, which promotes rapid zinc consumption.

These data demonstrate a great disparity between metal loss at sites with “good” compared to “poor” backfill soils. Extremely high rates of steel consumption were observed at the South Africa, SUNY Ramps, Caribou City, ID, and Las Vegas NV sites. Metal loss at these sites ranged from approximately 10 to 30 times greater than anticipated with current metal loss models and good backfill conditions (i.e., those that meet current AASHTO standards). The environment at the Brunswick, GA site did not allow the aluminum strips to become passivated, and a high loss rate was observed at this site.

Use of lower quality backfills does not always result in extremely poor performance, and in some instances reasonable performance may still be realized. Loss rates observed at five sites (i.e., Macon GA, the Sweet Home, Maple and Dodge Road sites in Amherst, NY, and I-85 Charlotte, NC) were high compared to the current metal loss model, but are not considered extremely high, and these walls are still in service. In general, backfills for these five walls have low resistivities, but chloride and sulfate concentrations are less than 500 ppm and 1000 ppm (compared to AASHTO limits of 100 ppm for chlorides and 200 ppm for sulfates), respectively. At sites where extremely high metal loss rates were observed, particularly poor backfills were used that had salt concentrations 50 times greater than allowed by AASHTO, or a low pH environment was present due to the nature of the fill, or soils high in organics were used, promoting microbial induced losses.

Further study is required to distinguish between conditions for which marginal backfills may be used with modified metal loss models and those circumstances which will likely result in extremely high rates of metal loss that cannot be tolerated. Absent such a study, backfill used in MSE walls must conform to the requirements of the AASHTO specifications.

Good Practice

There is data from approximately 100 MSE walls to document North American and European experience when generally good practice has been followed. European experience with MSE predates the practice in the United States and only weight loss measurements are available in the data collected from Europe. Measurements from North America include both physical observations such as weight loss, or loss of thickness, and electrochemical type nondestructive test (NDT) measurements including linear polarization resistance and half-cell potential.

Data from approximately 70 walls included in the “good” performance study are available for comparison to attributes of the database. Most of the walls studied for performance were constructed between 1975 and 1980 and most are located within the Southeast Region. The majority of the walls included in the performance study have backfill with resistivity higher than 10,000 ohm-cm and pH close to neutral, or are slightly alkaline.

An important consideration is the method or protocol by which metal loss data are obtained. Early loss monitoring practices (Darbin et al, 1978; Frondistou-Yannis, 1985; McGee, 1985; Ramaswamy and DiMillio, 1986; Whiting, 1986) involved exhuming and examining samples of reinforcements for evidence of metal loss, including loss of cross section. This technique is limited to reinforcements that are accessible and usually near the surface of the structure. Metal loss rate may be estimated from weight loss and thickness measurements, provided the original thickness or weight of the reinforcements and the original zinc thickness or weight are known. The loss rate is known to decay with time (Romanoff, 1957), and a catalog of measurements made at different times is required to assess the effect of time on rate of metal loss.

Other, more novel, techniques employ nondestructive electrochemical tests such as measurement of half-cell potential and linear polarization resistance (Elias, 1990). With these techniques, a large number of samples is monitored and frequent measurements may be collected. Half-cell potential measurements may be correlated with loss of zinc and used to monitor the condition of galvanized reinforcements. Coupons or dummy reinforcements assist in interpretation of half-cell potential measurements. Plain steel, galvanized and zinc coupons provide baseline measurements for comparison.

Linear polarization resistance measurements (LPR) measure the instantaneous rate of metal loss. Since loss history cannot be established from instantaneous measurements, reinforcement condition is difficult to determine from isolated LPR measurements. In older structures, discrete measurements may be particularly difficult to interpret, especially if the existing condition of the reinforcements is unknown. In addition, metal loss rate in an MSE structure may vary throughout the year due to transient temperature and moisture conditions, so LPR measurements should be performed during different seasons to estimate the average rate of metal loss. When measurements are taken throughout the service life of a wall, however, this technique can quantify the relationship between metal loss rate and time.

Ideally, protocols for condition assessment and metal loss monitoring of MSE walls should include both direct physical observations (i.e., weight loss/thickness measurements) and electrochemical tests such as LPR and half-cell potential measurements. However, very few studies include such complete data. Due to the different nature of the results, this White Paper considers metal loss observed from weight-loss measurements separately from measurements of polarization resistance.

Weight Loss. Salient details of 41 weight-loss measurements are listed in Table 3. Thirty-five sites included in Table 3 are from Europe and 6 are from the United States. The ages of exhumed reinforcements range from four to 20 years. All of the tested backfills included in Table 3 (for which the properties are known) meet the AASHTO (2002) electrochemical requirements. Due to the ages of the structures and the adequate thickness of zinc coating applied to the reinforcements, these data only represent zinc loss (i.e., zinc consumption is known to be less than the original zinc thickness). All of the weight loss measurements reported in Table 3 were performed on strip type reinforcements.

Figure 3 shows the weight loss measurements from the specimens listed in Table 3 and several metal loss models are superimposed for comparison with the data. With the exception of one data point from Pleyel, France (RECO, 1992) all data points in Figure 3 lie below the bilinear envelope defined by:

$V_1 = 15\ \mu m/yr$ for $t < 2$ yrs
$V_2 = 1\ \mu m/yr$ for $t > 2$ yrs.

This figure does not show the metal loss model suggested by Romanoff and Darbin because it was intended to model steel loss rather than zinc loss. The linear loss model specified by AASHTO (2002) is overly conservative relative to the data, leaving the linear loss model proposed by AMSE (and originally by Stuttgart University) as the appropriately conservative model that should be adopted.

Figure 4 shows metal loss observed for steel remaining after the zinc coating has been depleted from galvanized specimens. Figure 4 includes 16 data points as detailed in Table 4; of these, 13 are from various sites in Europe and 3 are from a single site in the United States. All the European data are from lightly galvanized steel reinforcements with a 30 μm layer of zinc that was consumed before the sample was retrieved for a weight-loss measurement. The specimens from the Oleans, CA site are of commercially galvanized wire mesh with a zinc coating weight of approximately 0.4 oz/ft^2 (≈17 μm thick). Two metal loss models are shown in Figure 4 along with the data; both follow the form described by Romanoff (1957). The top curve uses coefficients $k = 40$ and $n = 0.8$, as described by Elias (1990), to estimate the loss rate for carbon steel (i.e., not passivated by zinc oxide). The lower curve is the rate equation suggested by Darbin et al (1988) for metal loss from galvanized reinforcements in backfills with $R \leq 1000$ ohm-cm ($k = 25$, $n = 0.65$). The data in Figure 4 suggest that, for a zinc coating of 30 μm, steel loss after the zinc coating has been consumed commences at the rate for galvanized steel and not at the rate for bare steel. This phenomenon is due to the presence of zinc oxides on the surface of the steel and within the surrounding soil (TAI, 1977; RECO, 1992). However, the wire mesh samples with thinner zinc coating (estimated to have been consumed within 14 months) apparently commenced metal loss at a higher rate. This rate is closer to the loss rate anticipated for bare steel (not passivated by zinc oxide), suggesting that the initial zinc quantity on the wire mesh samples was insufficient to effectively passivate the steel.

In general, available data indicate that, for mildly to moderately aggressive backfill conditions, the base steel will be passivated by zinc oxide if the initial thickness of zinc coating is at least 30μm. However, this observation is based on limited observations of in-service reinforcements. The steel consumption observed from the Oleans, CA site was below expectations when passivation by zinc oxide was not considered in the estimation of service life. In fact, the sacrificial thickness of steel incorporated into the design of this wall did not consider any benefits of zinc beyond the 14-month service life assumed for the zinc coating. The data is useful, however, demonstrating the beneficial effect of the zinc coating on the rate of steel loss after the zinc is consumed.

Polarization Resistance Measurements. Figure 5 describes metal loss rates measured with the LPR technique at 16 sites located throughout the United States; the data is presented in Table 5. The backfill for these cases meets the criterion specified by AASHTO (2002). Only two of these sites have backfill with R < 9000 ohm-cm. The reinforcements included in the data range in age from one month to 19 years. Two of the sites utilized wire grids and the other sites utilized steel strip reinforcements. In all cases, half-cell measurements or visual observations were used to confirm that zinc was still present on the galvanized reinforcements. As shown on Figure 5, most of the data indicate that the loss rate for the zinc coating is less than 2 μm/yr.

One measurement at the Pensacola, FL site was 2.3 μm/yr. During demolition of the Pensacola wall in 2002, spotty zinc depletion was observed that might be attributable to poorly compacted backfill near the wall face. However, the majority of the reinforcements in this wall were in good condition, with zinc remaining after 24 years of service.

Half-Cell Potentials. In 1990 the North Carolina DOT (NCDOT) began installing monitoring stations during construction of MSE walls, and proceeded to monitor half-cell potentials of reinforcements and coupons at regular intervals (Medford, 1999). At each monitoring station, zinc bar and steel plate coupons were installed and reinforcements were wired for half-cell potential measurement. Initial readings were taken immediately after wall construction, with subsequent readings taken approximately once a year thereafter. Measurements included half-cell potentials of the coupons and reinforcements.

Figure 6 is an example of half-cell potential measurements recorded at a typical monitoring station. The record spans nearly 10 years from the date of wall construction in November 1992 until February 2002. Half-cell potentials of the zinc and steel coupons and of the wired reinforcement are compared. Initially (November 1992), the half-cell potentials of the reinforcement and zinc coupon are relatively close. As the zinc is consumed, the half-cell potential of the reinforcement approaches the half-cell potential of the steel coupon. Beckham (2005) reported the same phenomenon from his measurements on four walls in Kentucky, three of which had been in service in excess of 20 years. To date, the preponderance of the half-cell data tends to support the recommendation to reduce the zinc loss rate in the MSE metal loss model, but more data must be collected in order to draw a firm conclusion based on the half-cell potential method.

SUMMARY AND RECOMMENDATIONS

Summary of Observations

1. Structures investigated in the late 1990s were found to have more than half their original zinc coating remaining after 20 years in service. Similar findings by DOT owners throughout the United States demonstrate that the linear loss model currently used to design MSE structures is overly conservative. Metal loss measurements from approximately 150 observations, including direct physical examination of reinforcements

exhumed from in-service MSE walls, as well as electrochemical measurements including LPR, support the conclusion that the current AASHTO metal loss model for zinc is unnecessarily conservative.

2. The following zinc loss model fits the observed rate of zinc loss:

   V_1 = 15 µm/yr for t < 2 years
   V_2 = 2 µm/yr for t > 2 years.

   For galvanized reinforcements meeting the requirements of ASTM A123, the zinc loss model determines a 30 year life of zinc within backfill meeting the requirements for MSE walls as specified by AASHTO. This life is approximately twice the anticipated service life for zinc based on the current AASHTO zinc loss model, but is still a conservative estimate.

3. Half-cell potential measurements used to evaluate the condition of reinforcements also support the conclusion that it takes at least 30 years for zinc to be consumed in backfills typical of good construction practice for MSE walls.

4. Observed rates of steel loss following loss of zinc indicate that the steel is passivated by the zinc oxide and that subsequent steel loss occurs at the reduced rate expected for steel that has been galvanized with 86 µm of zinc.

Proposed Change to Metal Loss Model: Reduced Zinc Consumption

As discussed by Elias (1990), the long-term zinc loss rate proposed by Stuttgart University in 1980 for both non-saturated and saturated soils with resistivities greater than 1000 ohm-cm is 2 µm/yr. This is the loss rate applicable after applying an accelerated rate for the first two years. For no apparent reason, however, the 2 µm/yr loss rate was changed to 4 µm/yr when the AASHTO specifications were written. In view of data presented herein, it is clear that the zinc loss rate should have been set at the Stuttgart-recommended rate of 2 µm/yr. Using this loss rate, the effective life of the 86 µm zinc coating is 30 years instead of only 16 years.

The totality of MSE experience to date justifies the following loss rates for design:

Loss of zinc (first 2 yrs)	15 µm/yr
Loss of zinc (to depletion)	2 µm/yr
Loss of steel (after zinc depletion)	12 µm/yr

Adopting a more realistic zinc loss model will allow state transportation agencies to realize significant cost savings. The proposed zinc loss model will reduce the required thickness of sacrificial steel by 336 µm. For 4 mm thick reinforcing strips and for 7.6 mm (W7) diameter wire mesh reinforcements, this reduced sacrificial thickness will result in approximately a 10%

savings in steel cost where stress controls the design. This change clearly contributes to meeting the second and fourth Grand Challenges in the AASHTO *Strategic Plan for Bridge Engineering*.

RECOMMENDED CHANGE TO AASHTO METAL LOSS MODEL

Data presented in this White Paper was collected from MSE structures that have been in service for up to 28 years. These data demonstrate relatively low rates of metal loss when good practice is followed, including the use of backfill meeting the current AASHTO requirements. Specifically, the data show that approximately half of the original 86 μm zinc thickness remains after 20 years in service. This data strongly supports the conclusion that the current zinc loss model is overly conservative and that revisions to the AASHTO specifications are warranted.

Based on the data presented in this White Paper, it is proposed to revise the AASHTO metal loss model by changing the zinc loss rate from 4 μm/yr to 2 μm/yr for the period from two years of service to zinc depletion. The history of the loss model and the AMSE proposal to AASHTO are summarized below:

History and Proposed Revision to AASHTO Metal Loss Model for MSE Walls

Model / Time Period	Stuttgart University (1980)	Current AASHTO* (since 1992)	**AMSE Proposal to AASHTO**
Loss of zinc (first 2 years)	15 μm/yr	15 μm/yr	**15 μm/yr**
Loss of zinc (to depletion)	2 μm/yr	4 μm/yr	**2 μm/yr**
Loss of steel (after zinc depletion)	12 μm/yr	12 μm/yr	**12 μm/yr**
Predicted Zinc Life	**30 years**	**16 Years**	**30 Years**

*Arbitrary change introduced in AASHTO Specifications:

- Loss rate *increased* from 2 to 4 μm/year
- Therefore, zinc life *reduced* from 30 to 16 years

A zinc loss rate of 2 μm/yr for design of MSE walls is not a new idea. This zinc loss rate was recommended by Stuttgart University in 1980 and was incorporated into the predecessor of the current AASHTO specifications by Task Force 27 of the AASHTO-AGC-ARBTA Joint

Committee in 1990 (Task Force 27, 1990). Despite this recommendation, the zinc loss rate was arbitrarily changed to 4 μm/yr when it was included in the AASHTO Standard Specifications for Highway Bridges in 1992.

Performance data collected during 34 years of service and presented in this White Paper support the proposed revision of the zinc loss rate from 4 μm/yr to 2 μm/yr. This change is consistent with Grand Challenge 2, Optimizing Structural Systems, and Grand Challenge 4, Advancing the AASHTO Specifications of the AASHTO S*trategic Plan for Bridge Engineering*. The Association for Metallically Stabilized Earth requests that this revision be adopted by the AASHTO T-15 Subcommittee on Substructures and Retaining Walls for incorporation into the AASHTO LRFD Bridge Design and other applicable Specifications.

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Hilfiker Retaining Walls, www.hilfiker.com
Maccaferri, Inc., www.maccaferri-northamerica.com
SSL, LLC, www.mseplus.com
T & B Structural Systems, www.tandbstructural.com
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FIGURES
AND
TABLES

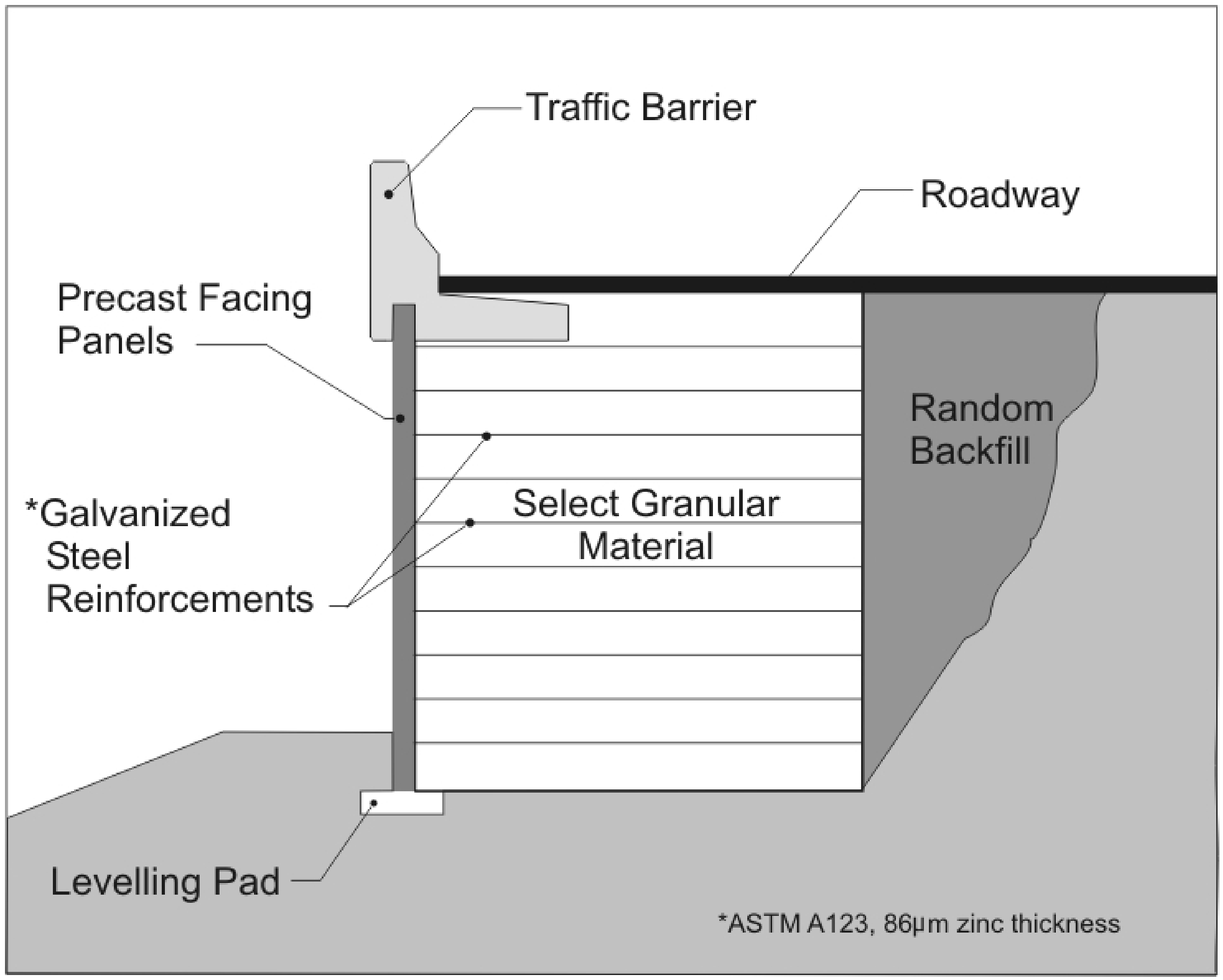


Figure 1 Typical Section of an MSE Wall

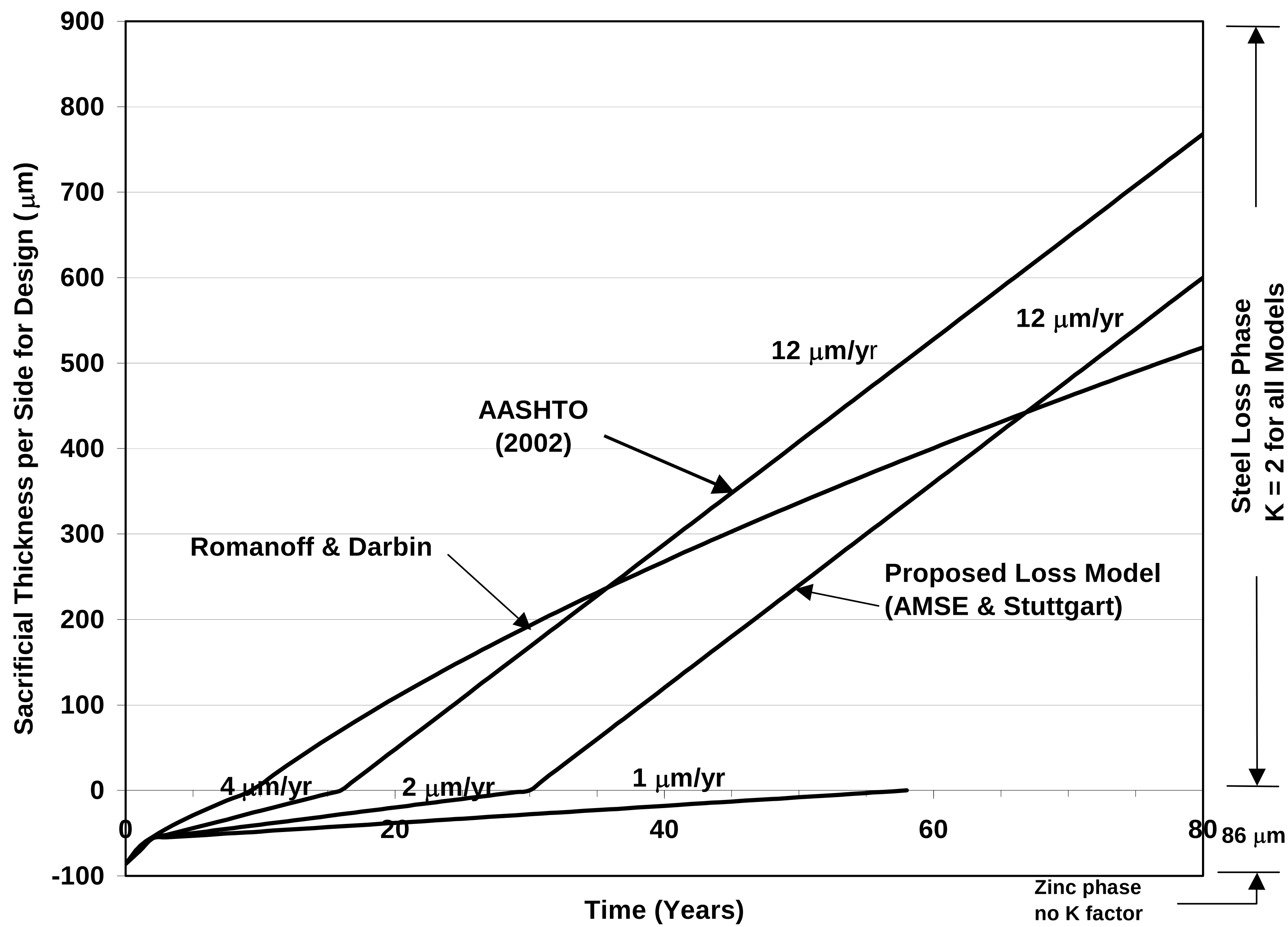


Figure 2 Comparison of Metal Loss Models for AASHTO-Specified Backfill; R≥3000 ohm-cm

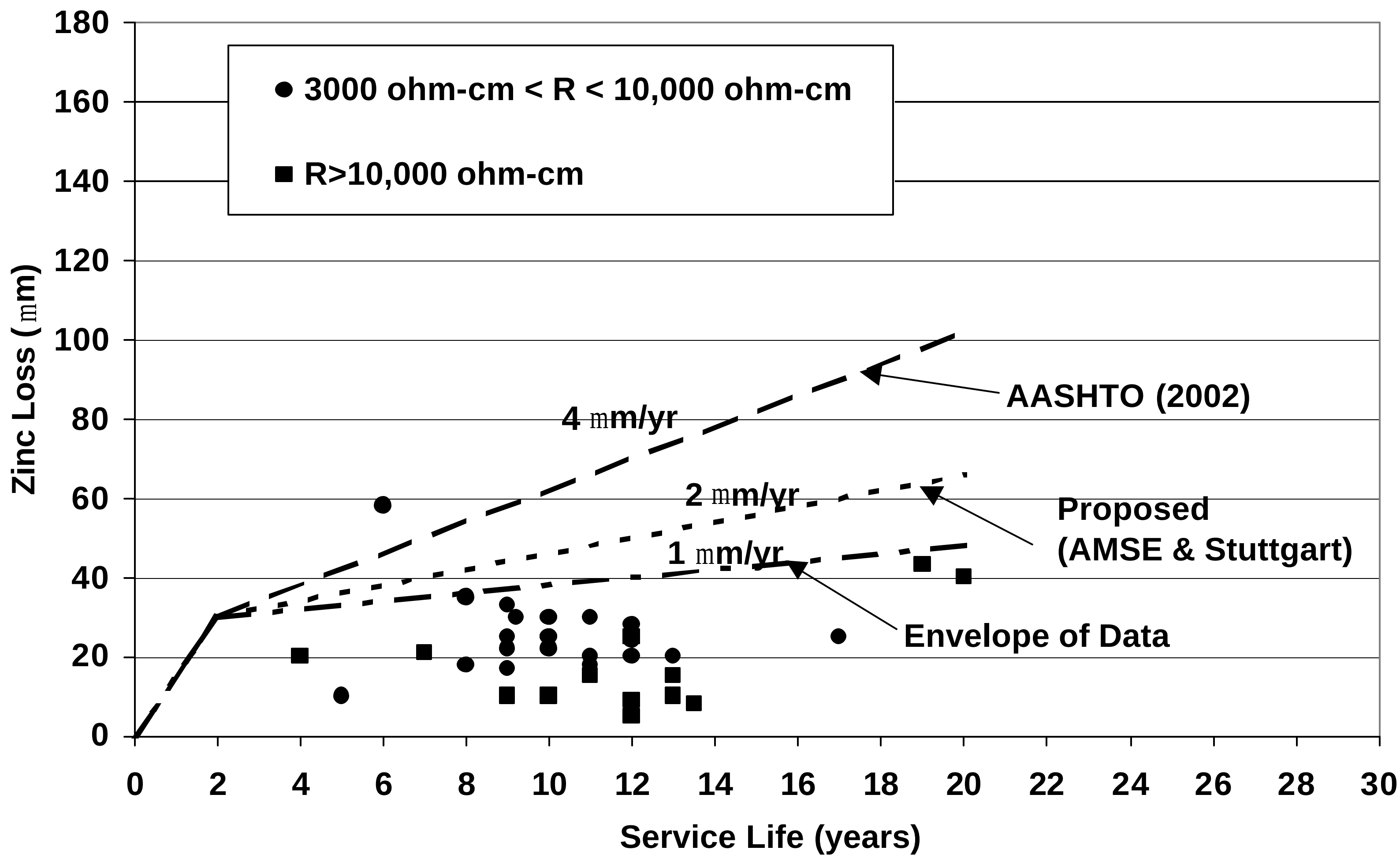


Figure 3 Observations of Zinc Loss from Weight Loss Measurements

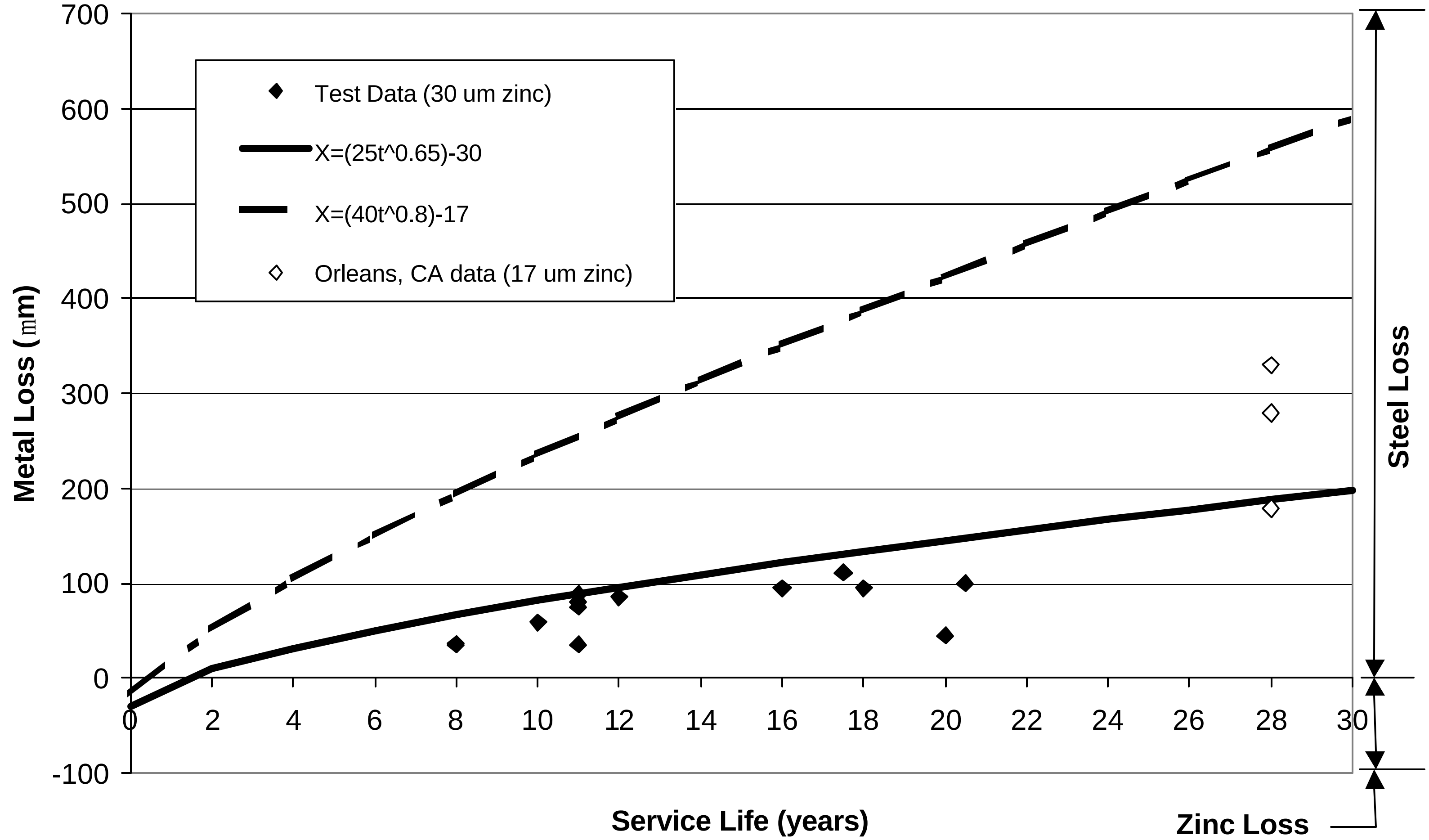


Figure 4 Metal Loss Based on Weight Loss Measurements

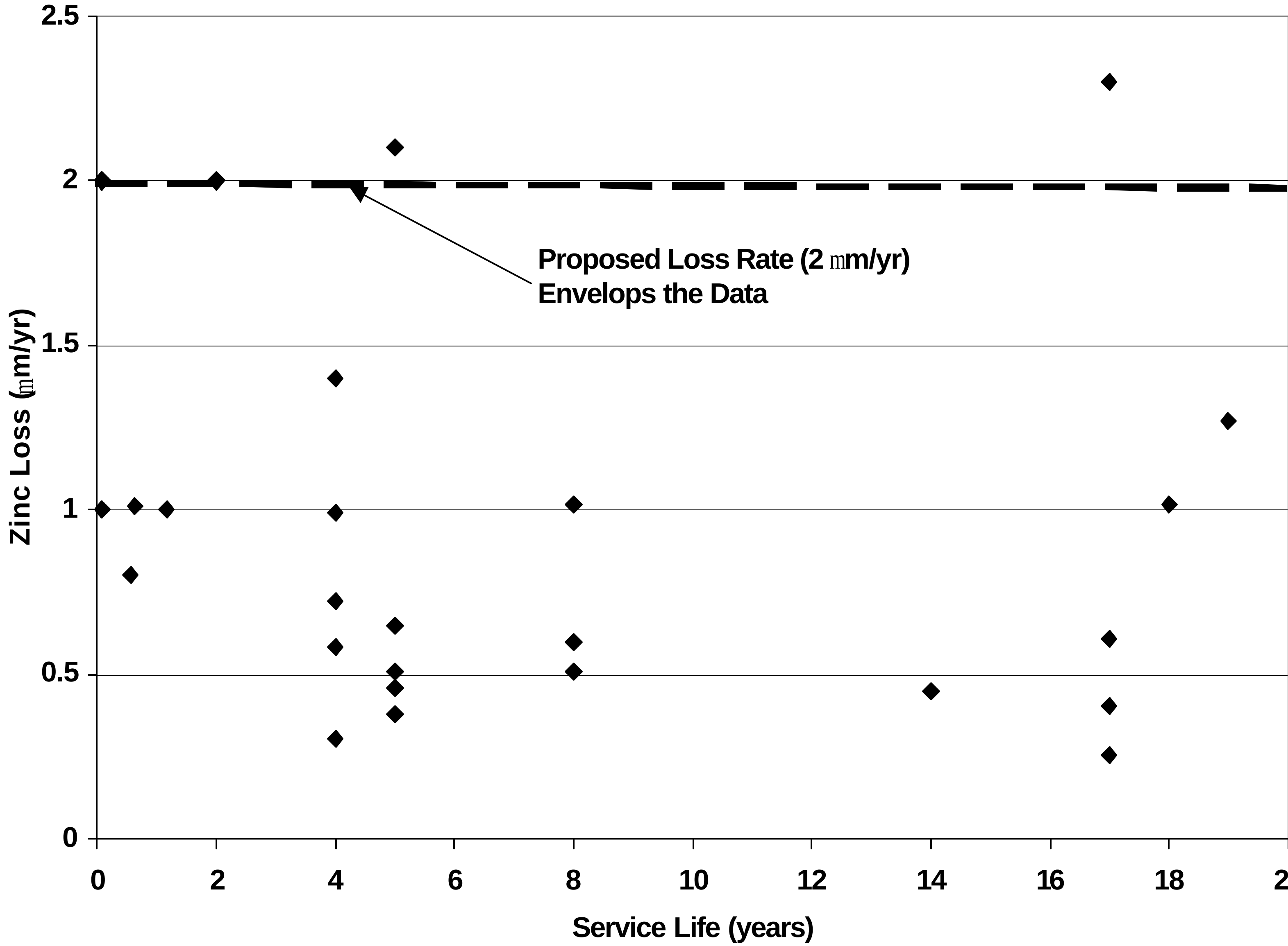


Figure 5 Zinc Loss Rate from LPR Measurements

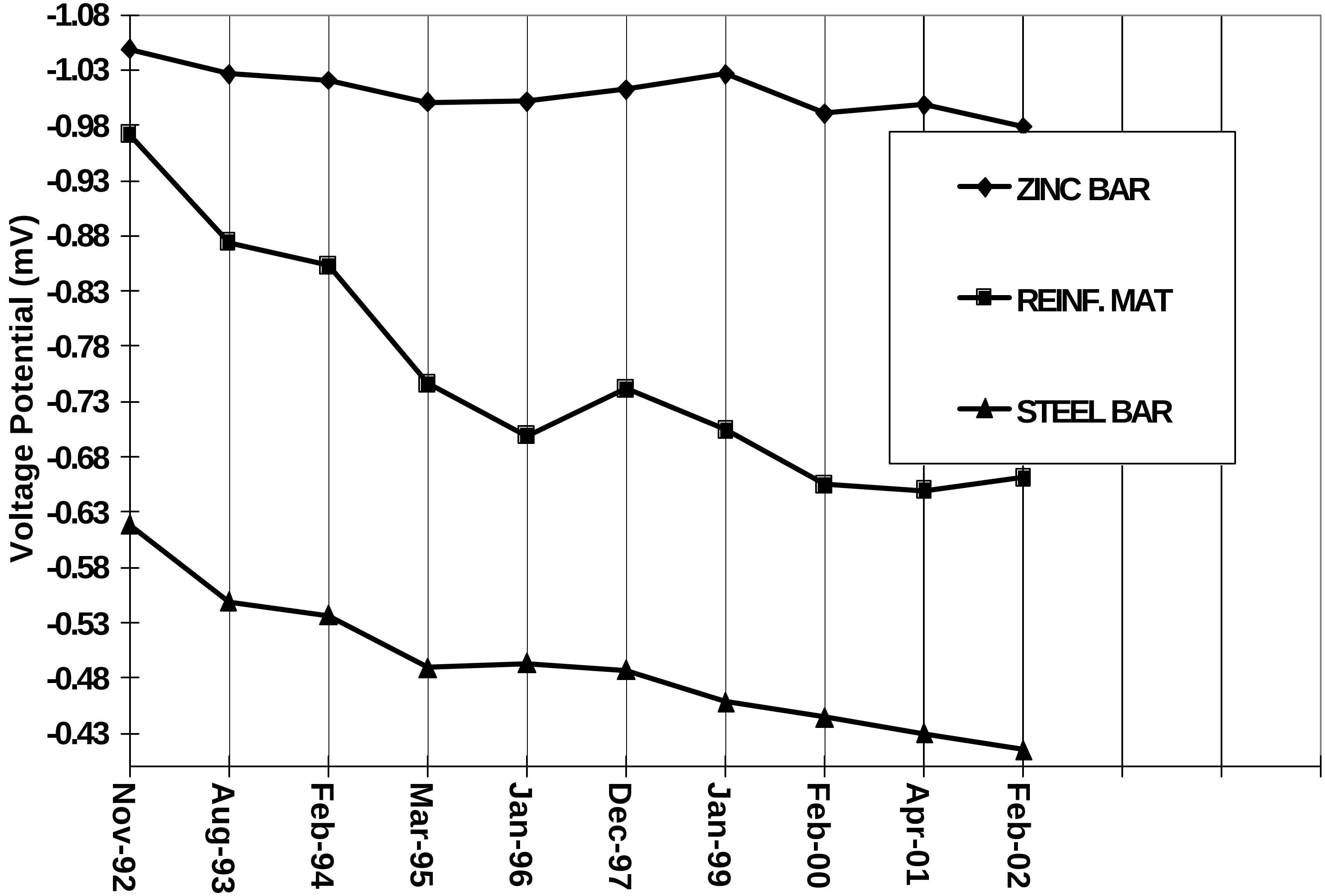


Figure 6 Time History of Half-Cell Measurements (Medford 1999)

TABLE 1 MSE Walls Where Poor Performance is Documented

Study	Source	Sample Location	Backfill Properties				
			Description	Resistivity (ohm-cm)	pH	Cl (ppm)	SO_4 (ppm)
1	Blight & Dane (1989)	South Africa	Clayey sand	500	5	5000	800
2	McGee(1985), Frondistou-Yannis (1985), Whiting (1986)	Brunswick, GA	Fine sand with 2% to 12% organics	100	4.84	1435	310
3	Deaver (1992)	Macon, GA	Loose sand[1]	3800	5.1		16
4	Elias (1990), Wheeler (1999, 2002)	Sweet Home Road[2]	Slag and cinder ash	426	11.4	499	742
5	Elias (1990)	SUNY Ramps[2]	Cinder ash	40	3.7		2700
6	Elias (1990), Wheeler (2002)	Maple Road[2]	Crushed sandy gravel	700		400	500
7	Wheeler (1999, 2002)	Dodge Road[2]	Slag and cinder ash	426	11.4	499	742
8	Medford (1999)	I-85, Charlotte, NC	Screenings – iron-rich soils	440	6.1		
9	Berkovitz (1997), personal communication	SR 34, Caribou City, ID	Silty gravel	820	9.9	890	1770
10	Fishman, et al (2006)	I-515, Las Vegas, NV	Silty coarse sand	700	9	500	10000
11	Frondistou-Yannis (1985), Whiting (1986)	Lovelock, NV	Local source – nonhomogeneous	3750	> 10	30	100

[1]Reinforcement recovered from within embankment cap material
[2]Amherst, NY

TABLE 2 Summary of Metal Loss at Sites with Poor Performance

Study	Sample Location	Year Const.	Age[1] (yrs)	Metal Loss Measurement
1	South Africa	1979	8	100 µm/yr
2	Brunswick, GA[2]	1974	9	800 µm (local corrosion)
3	Macon, GA	1978	9	> 70 µm/side
4	Sweet Home Road	1981	7, 21	6 µm/yr, 18 µm/yr
5	SUNY Ramps	1981	7	200 µm/yr
6	Maple Road[3]	1985	3	8 µm/yr
7	Dodge Road	1981	21	22 µm/yr
8	I-85, Charlotte, NC	1978	14	> 86 µm/side – zinc depleted
9	SR 34, Caribou City, ID	1978	24	> 750 µm/side – broken tie strips
10	I-515, Las Vegas, NV[4]	1985	19	65 µm/yr
11	Lovelock, NV	1974	11	100 µm/yr – steel loss

[1] Age at testing
[2] Aluminum strips
[3] Galvanized grids
[4] Plain (black) steel grids

TABLE 3 Summary of Zinc Loss Measurements

Sample Location		Year Const.	Age[1] (yrs)	Thickness Loss/Side (µm)	Resistivity (ohm-cm)	pH	Cl (ppm)	SO_4 (ppm)
United States	I-66, Arlington, VA	1979	19	43	19090	4.9		
	SR 101, San Luis Obispo, CA	1980	20	40	54000	7.1		
	I-16, Macon, GA	1978	9	22				
	I-16, Macon, GA	1978	9	33				
	Marta, Atlanta, GA	1976	7	21	100000	7	1.6	10
	Vail Pass, CO	1974	9	10	10000	8	6.7	10
France	Vigna – A 8	1969	10	10	14340	7.3	4	25
	La Giraude – A 8	1969	13.5	8	44500	7.2	1	19
	La Croix	1968	17	25				
	Rouen	1969	12	5	20000	7.7	5	19
	Strasbourg	1969	13	20				
	Avignon	1971	11	20				
	Palaiseau	1971	12	20	5220	7	4	33
	Orsay	1971	12	25	35130	7.1		
	Strasbourg – Roc. Ouest	1970	13	15	69500	8.4	2	8
	Saint Jorioz	1970	13	10	18600	8.45	2	
	Annecy	1973	12	24				
	Givors	1971	12	25	19550	7.55	3	7
	Tours	1972	11	18	5930	7.8		
	Saint Fereal	1972	11	15	33330	7.5	2	13
	Trappes	1972	11	20	9800	6.8	3	34
	Le Paillon – Ms 21	1973/74	10	22	6935	7.8		
	Niort	1973	12	28				
	Corsel	1972	11	15	3270	6.85	4	122
	Le Pavillon – Oa 76b	1974	9	25	4800	7.6		
	Vallon Des Bimes	1972	9.2	30	7850	7.8		
	Evry	1972	10	25	5400	7.2	26	6
	Lille	1972	11	30	7410	8.4		
	Landemeau	1980	8	35				
	Tours – Pt. Mirabeau	1973	10	30	5650	7.8	0	45
	Corbeil – Gilardoni	1972	10	25	3400	6.5	23	115
	Harpleur	1973	10	25	7120	8.25		
	Villeneuve Loubet	1974	11	34	2110	7.35		32
	Toulon – B 52	1974	9	17				
	Tauves	1976	5	10				
	Carrefour Pleyel	1979	6.5	58				
	La Defense	1975	10	30	3500	7.8	43	28
	Connaught Interchange	1981	8	18	3250	5.6	52	
	Pleyel	1979	6	58				
	Saint Jorioz	1970	4	20	18600	6.45	2	
	Rehm	1980	12	9	13500	8.4	20	290

[1]Age at testing

Table 4 Summary of Steel Loss Measurements

Sample Location	Year Const.	Age (yrs)	Thickness Loss/ Side (µm)	Resistivity (ohm-cm)	pH	Cl (ppm)	SO_4 (ppm)
Vallon Des Grottes	70	18	95	7460	7.7	3	26
Sete	72	11	80	2730	7.7	3	28
Merlebach	72	11	75	12900	7.45		
Dunkeroue	70	12	85				
Brest	72	11	35	12890	7.6		
La Brecoue	72	8	35	17550	8.55		
Franconville	72	11	88	4760	7.6		
Laval	74	10	59	2690		2	198
Perpignan	76	8	36				
Franconville - A15	73	20.5	100				
Saint Isidore Le Paillon	73	20	45	16660	8.65		
Noeud routlier La Brecque	72	17.5	111	1530	6.85	6	960
Vallon Des Grottes - Nice	70	16	95	7490	7.7	3	27
Orleans, CA	75	28	179	8677	7	< 2	5
Orleans, CA	75	28	279	13310	7	< 2	14
Orleans, CA	75	28	330	12344	7	< 2	5

TABLE 5 Summary of LPR Measurements

Source	Year Const.	Age[1] (yrs)	Rate (µm/yr)	Resistivity (ohm-cm)	pH	Cl (ppm)	SO_4 (ppm)
North Carolina (Medford, 1999)							
I-40/NC-191 Farmers Market	1986	11	2.54	2290	5.2		
I-40 EBL Old Fort Mountain	1979	18	1.02	10650	7.2		
I-85 Mulberry Church Road	1978	19	1.27	10380	6.7		
NC-51 Mathews Bypass	1989	8	1.02	4410	6.8		
NC-54 Chapel Hill Bypass	1989	8	0.51	10940	7.5		
New York (CC Technologies, 2000)							
16 in-service reinforcements	2000	<1	1 to 2	9000	8.9	>10	>10
Florida (Sagues, 1998, 1999)							
Brickell Avenue – South	1996	<1	1.00	33750	9.2	5.2	9
Brickell Avenue – North	1996	<1	0.80	41750	9.1	12.7	30
Howard Franklin – 7	1992	4	0.58	11000	8.5	8.8	0
Howard Franklin –11	1992	4	0.99				
Howard Franklin – 15	1992	4	0.72	22500	7.7	55	2.1
Howard Franklin – 17	1992	4	0.30	21000	8.7	1.5	0
Palm City – 1	1991	5	0.38	45000	9.1	1.4	0
Palm City – 5	1991	5	0.65	38000	9.1	3.5	0
Palm City – 14	1991	5	0.46	41000	9.2	2.5	0
Palm City – 28	1991	5	0.51				
Pensacola – 17	1979	17	2.29				
Pensacola – 23	1979	17	0.61	24500	7.5	4.5	25.2
Pensacola – 44	1979	17	0.41	17000	8.7	6.9	25.8
Pensacola – 62	1979	17	0.25	18750	8.8	8.8	0
Veteran’s Expressway		4	1.40				
St. Lucie Blvd.		5	2.10				
Acosta Bridge		8	0.60				
SR 200		14	0.45				
FHWA (Elias, 1990)							
Algonquin, Ill., Site 4	1986	1	1.00	15000		0	0
Algonquin, Ill., Site 5	1986	1	1.00	15000		0	0
Preston, CA		2	2.00	2800	5.1	40	69

[1] Age at testing

APPENDIX A

SURVEY FORM

I. PROJECT INFORMATION

1. Project Name (as it appears on the project plans):

____

____

____

2. Internal Project Number:

Hilfiker-No. ____________

Maccaferri-No. ____________

RECO-No. ____________

SSL-No. _____________

TBSS-No. _____________

3. Owner:

☐ State DOT

☐ Municipality

Federal Agency

☐ USACOE

☐ Forest Service

☐ Other _____________________________________

☐ Private

4. Location:

State:___________________

County:______________________________________

Locality:____

5. Date Built (year) _________

6. Number of Backfill Sources:______

(One or more backfill sources are utilized on a project. Assign a number to each source for use in Items 27 and 28.)

II. WALL INFORMATION

7. Wall Name: (e.g. east abutment for CR 16 over I-95, northeast wing wall for CR 16 over I-95, retaining wall along east side of off ramp from Main St. to I-95)

____

____

8. Wall Number:
(identify each wall associated with a project)

Internal Project No. from Sheet I:

Hilfiker-No. ____________
Maccaferri-No. ____________
RECO-No. ____________
SSL-No. ____________
TBSS-No. ____________

Assign a unique number to each wall on a given project:

Wall No. ______________

9. Section Geometry:

☐ cut
☐ fill
☐ varies
☐ unknown

10. Structure Supports:

☐ slope
☐ interstate or state highway
☐ local highway
☐ abutment (piles)
☐ abutment (spread ftg)
☐ railroad
☐ building
☐ parking lot
☐ median
☐ other

11. Structure Toe, i.e. what is in front of the structure?

☐ road
☐ slope
☐ stream channel
☐ waterfront
☐ other

12. Submergence:
Check One:
☐ none
☐ Submerged
☐ Intermittently Wetted

Water in submerged zone:
Check One:
☐ Fresh Water
☐ Marine Environment
☐ Brackish Water

13. Deicing Salts:

Are deicing salts used above the structure or within the splash zone?
☐ yes
☐ no
☐ unknown

Is an impermeable membrane above the backfill?
☐ yes
☐ no
☐ unknown

14. Environmental factors

Is groundwater contaminated?
☐ yes ☐ unknown
☐ no

Is acid mine drainage (AMD) prevalent?
☐ yes
☐ no

Is there a chemical or manufacturing plant adjacent to the site?
☐ yes
☐ no

15. Is there a source of underground stray current?
☐ No
☐ underground transmission lines
☐ welding shop
☐ electric train tracks

16. Max. Height: ____ ft.

17. Min. Height: ____ ft.

18. Length: ________ ft.

19. Aspect Ratio:
(Reinforcement length divided by wall height)
___ %

20. Surface Area:
______________ sq. ft.

21. Function:
☐ Abutment
☐ U-Wingwall
☐ Flared Wingwall
☐ In-Line Wingwall
☐ Retaining Wall

22. Exposure:
☐ N to E
☐ E to S
☐ S to W
☐ W to N

23. Facing Type:
☐ cruciform ☐ gabion
☐ rectangle ☐ wire
☐ square ☐ other

24. Nominal Facing Size:
____

25. Retained Slope:

Slope Type:
☐ level
☐ broken
☐ infinite

Slope Inclination (if applicable):
☐ flatter than 3H:1V
☐ between 3H:1V and 2H:1V
☐ steeper than 2H:1V

Vegatated Backslope
☐ yes
☐ no

26. Reinforcement Type & Size (Choose One):

☐ Strip

a) Galvanization:

ASTM Spec. ☐ A-525 ☐ A-123 ☐ none

zinc coating __________ ☐ µm ☐ oz/ft^2

as: ☐ specified ☐ measured

b) dimen: _______ mm x ________ mm

c) Steel Grade ASTM: ☐ A-446 ☐ A-572

☐ Grid or Mesh

a) Corrosion Protection:

☐ none ☐ galv. ☐ galv.+ PVC ☐ other

Galvanization (if applicable):
ASTM Spec. ☐ A-123 ☐ A-641
zinc coating:________ ☐ µm ☐ oz/ft^2
as: ☐ specified ☐ measured

b) ☐ grid ☐ mesh

☐ grid size:
long. = _____ gage @______ in spacing
trans.= _____ gage @ ______ in spacing
or
WWF =_____x_____ -W_____ x W_____
(long space (in) x trans. space. (in) – W (long.) x W (trans.))

☐ mesh size:
mesh type = _____x_____
mesh opening = _____x_____ mm

c) Steel Grade __________

d) Connection Type: _________________

27. Backfill Source #Use the number assigned to each source utilized on a project (see Items 6 and 28):

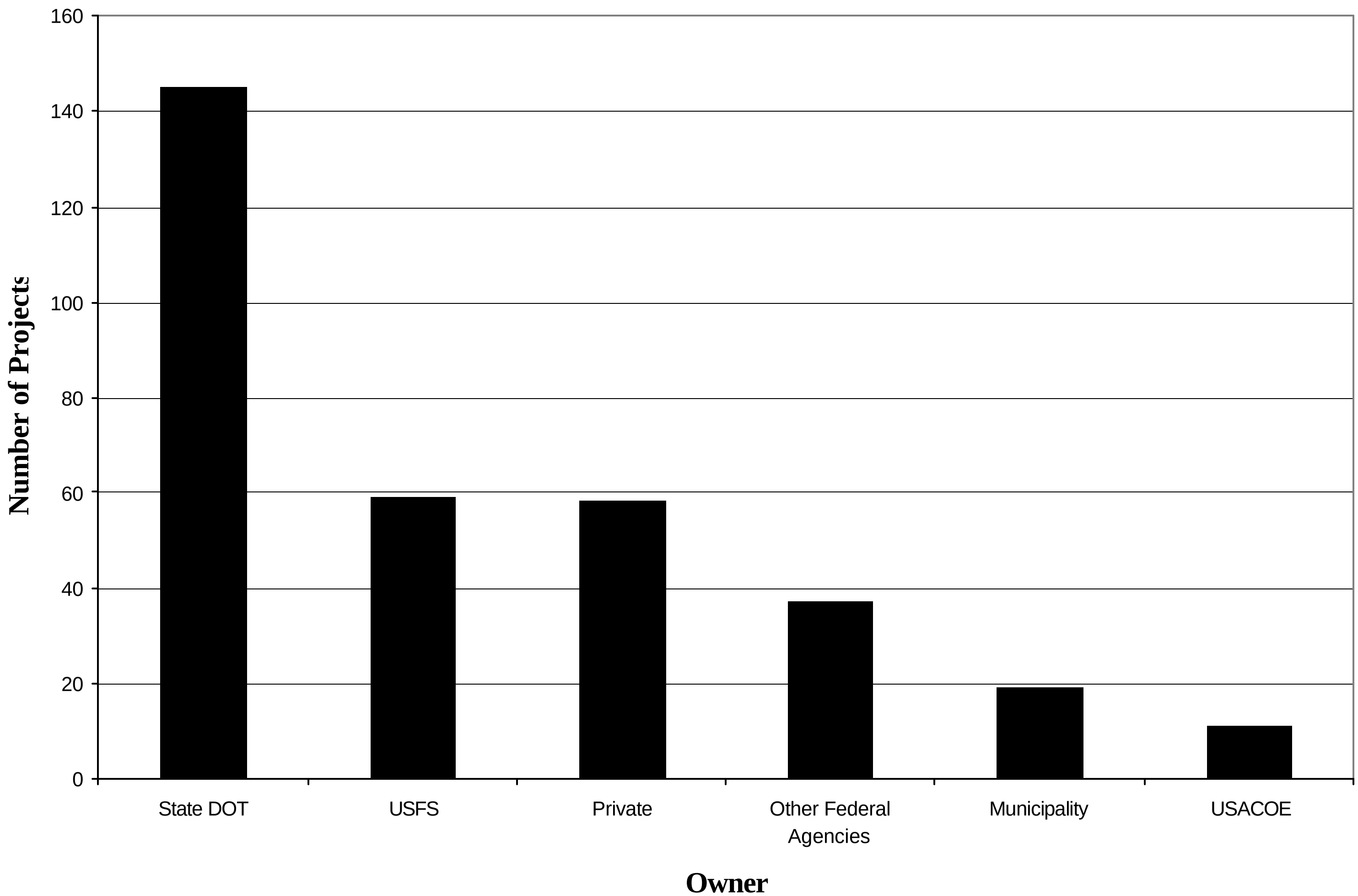
Backfill No. ____________________ (Sources are described in Section III.)

III. BACKFILL INFORMATION

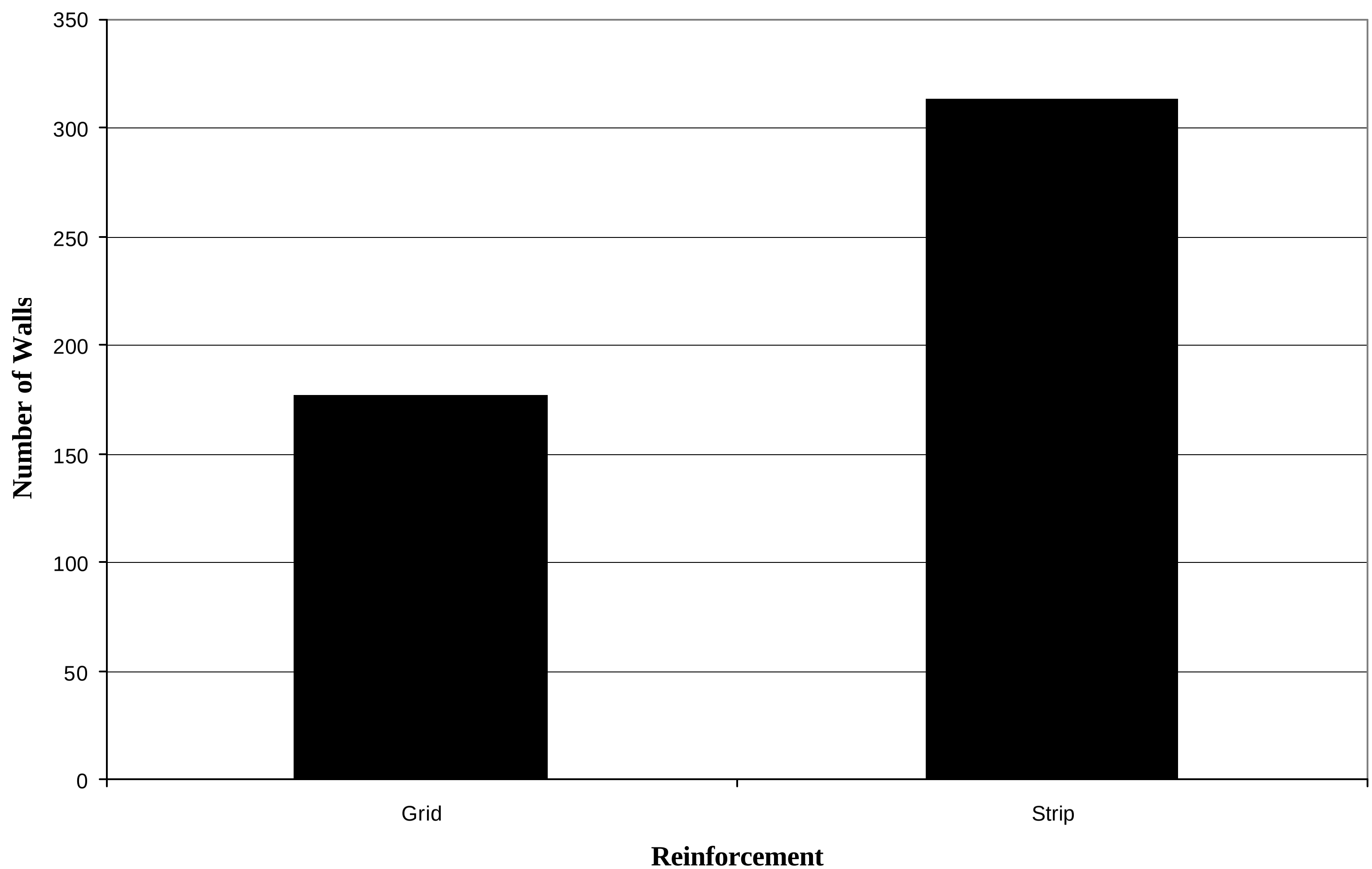
28. Backfill Source #: (identify each backfill utilized on a project) Internal Project No. from Sheet I: Hilfiker-No. ____________ Maccaferri-No. ____________ RECO-No. ____________ SSL-No. ____________ TBSS-No. ____________	Assign a unique number to each backfill utilized on a given project: Backfill No. ________________
29. a) Origin: ☐ manmade (screened or combined) ☐ sand or gravel pit ☐ bank run ☐ crusher run ☐ lightweight fill ☐ slag or cinder ash ☐ other ______________________	
b) USCS ☐ not available ☐ GW ☐ SW ☐ GP ☐ SP ☐ GM ☐ SM ☐ GW-GM ☐ SW-SP ☐ GP-GM ☐ SP-SM	**c) Supplier and Designation** (e.g. AASHTO No. 57 Stone from Frontier, Inc.) __________________________________ __________________________________ ☐ not available
30. Backfill Drainage: Drainage blanket behind wall? ☐ yes ☐ no	Perforated pipe at base of wall? ☐ yes ☐ no
31. Physical Properties: Organics: ____% Fines Content: ___%	**32. Electrochemical Properties:** pH: ____ Resistivity: __________ Ω-cm Sulfates: _______ ppm Chlorides: _______ ppm

APPENDIX B

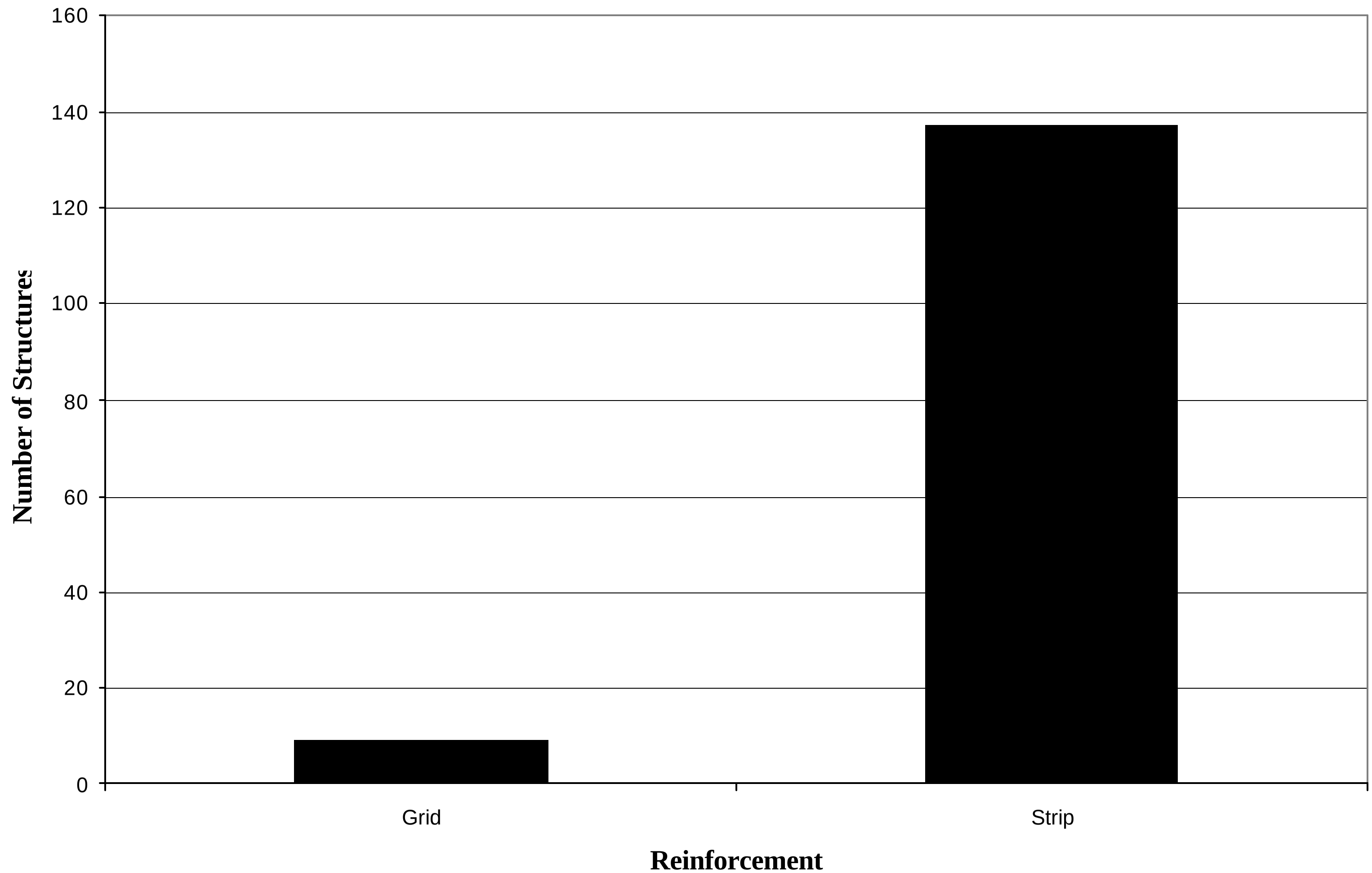
DEMOGRAPHICS OF MSE WALLS IN DATABASE



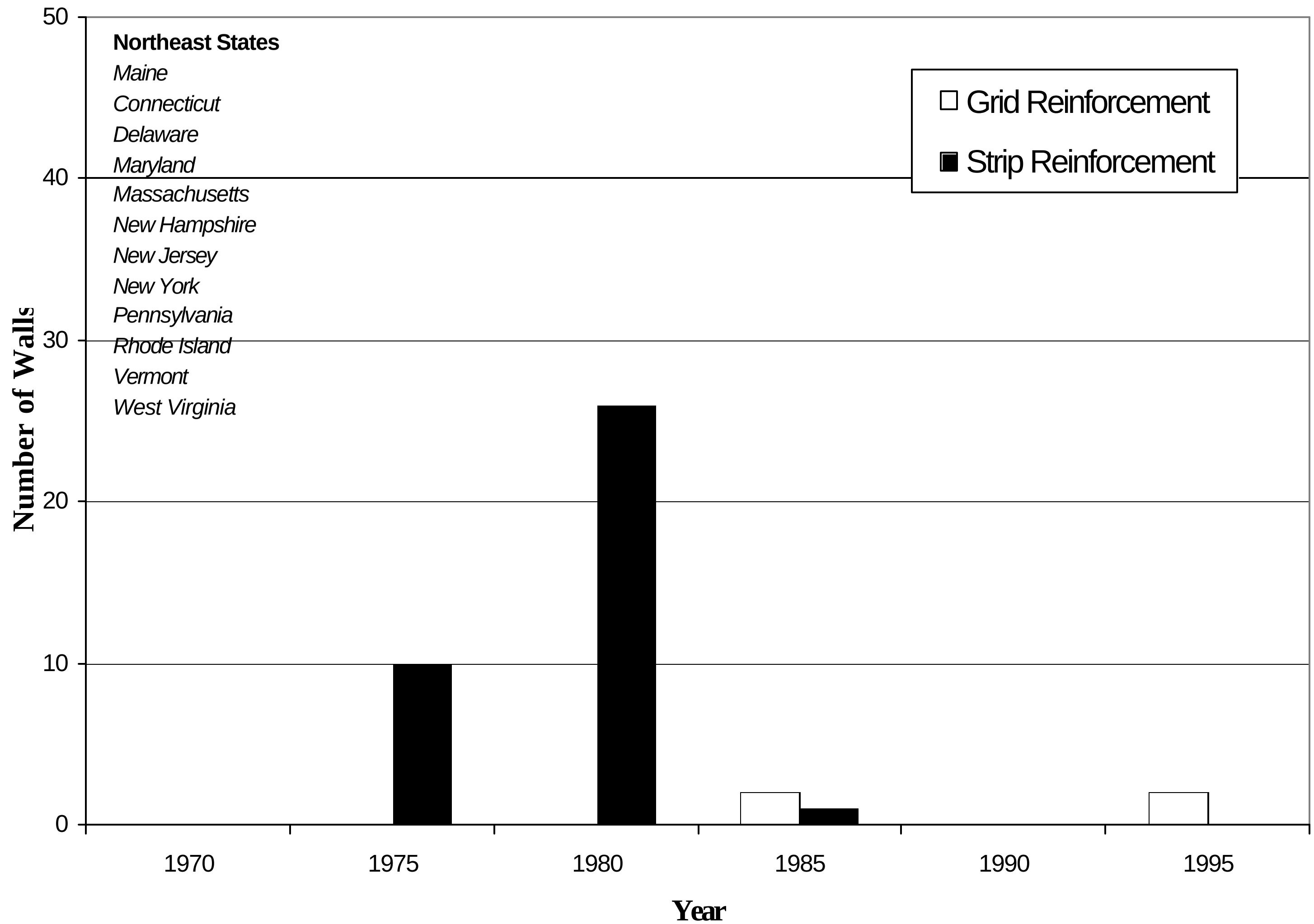
Owners of MSE Walls Constructed in the United States



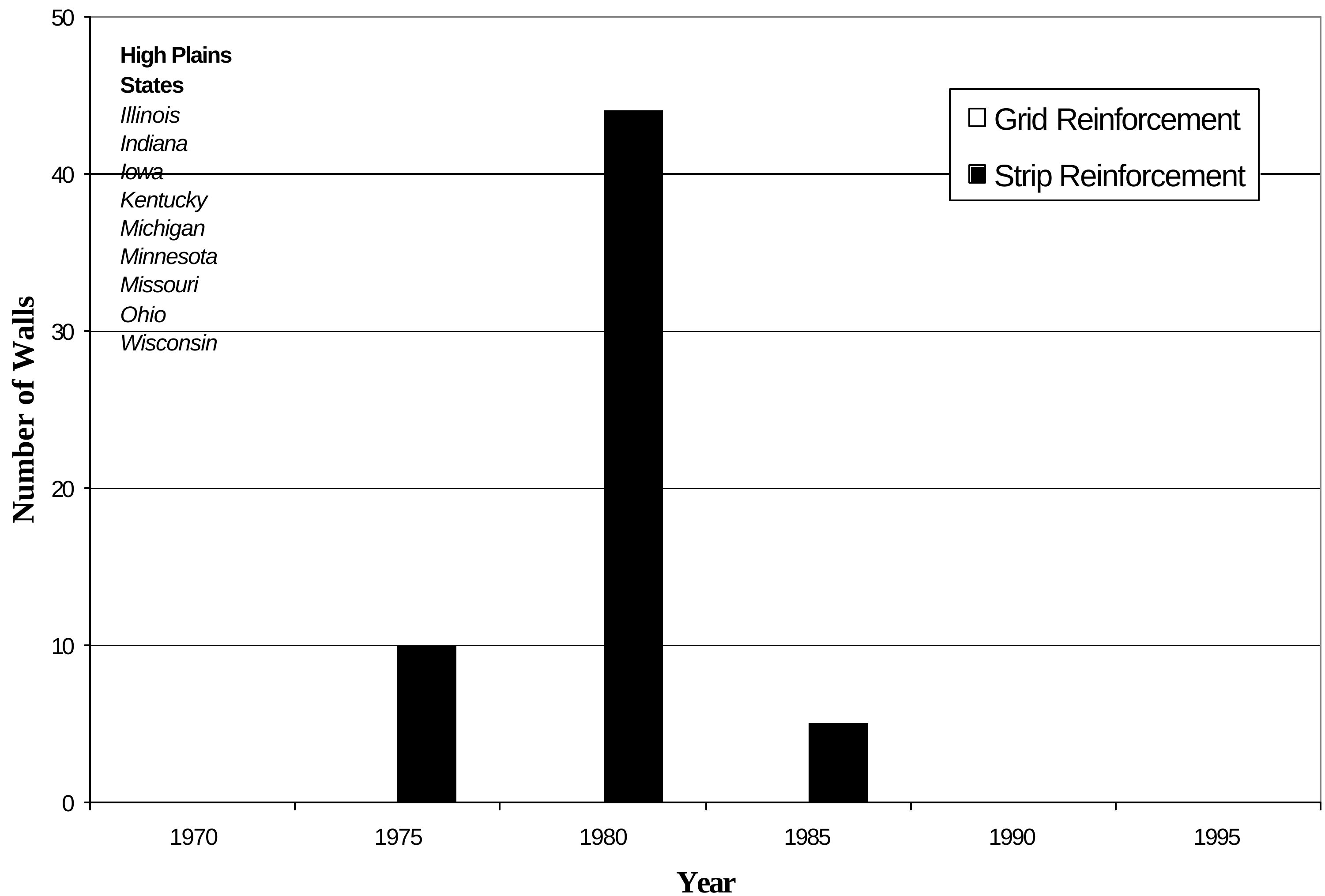
Comparison of the Use of Grid vs. Strip Reinforcements for Free Standing Retaining Wall



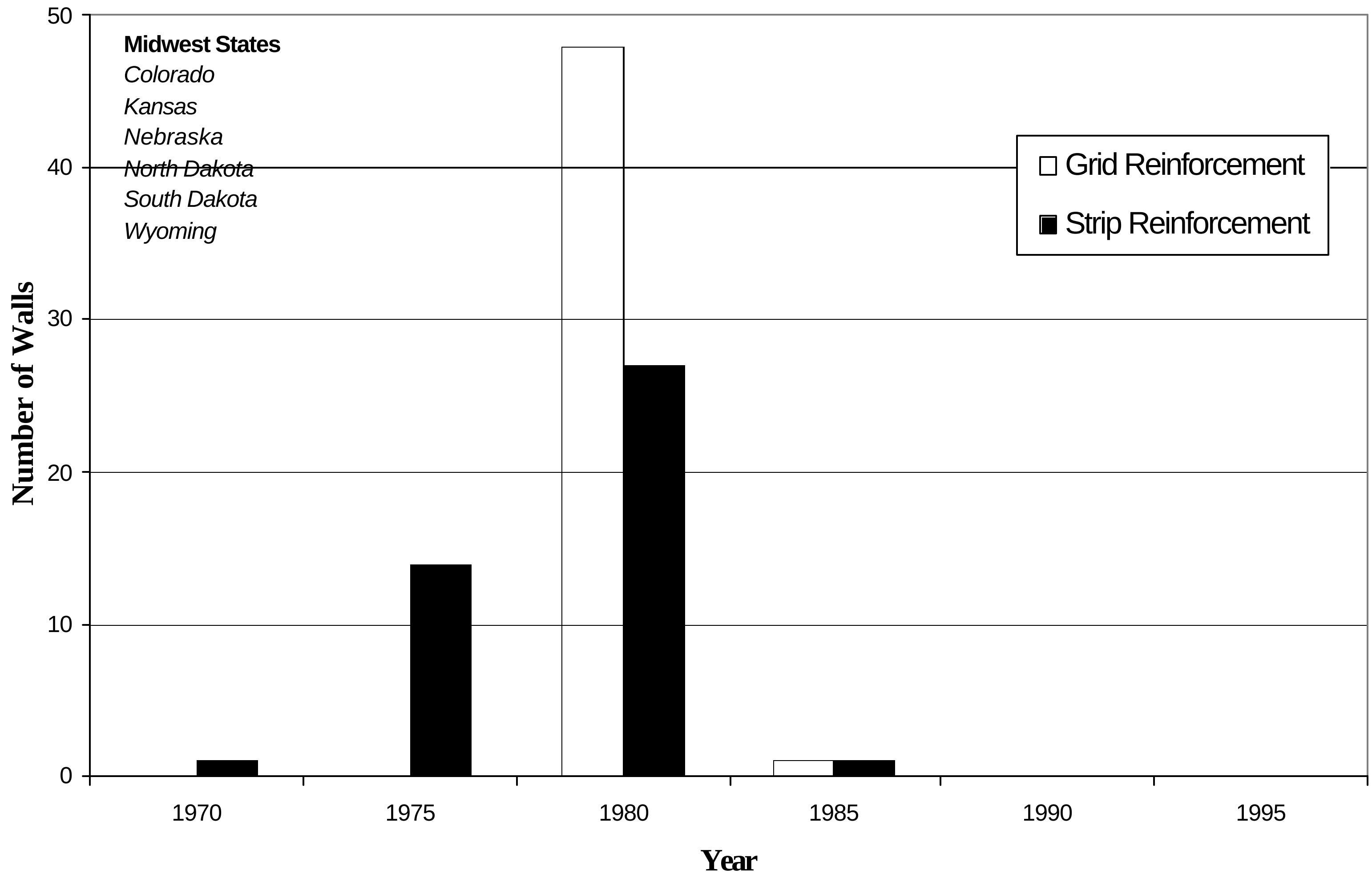
Comparison of the Use of Grid vs. Strip Reinforcements for Bridge Abutment/Wing Walls



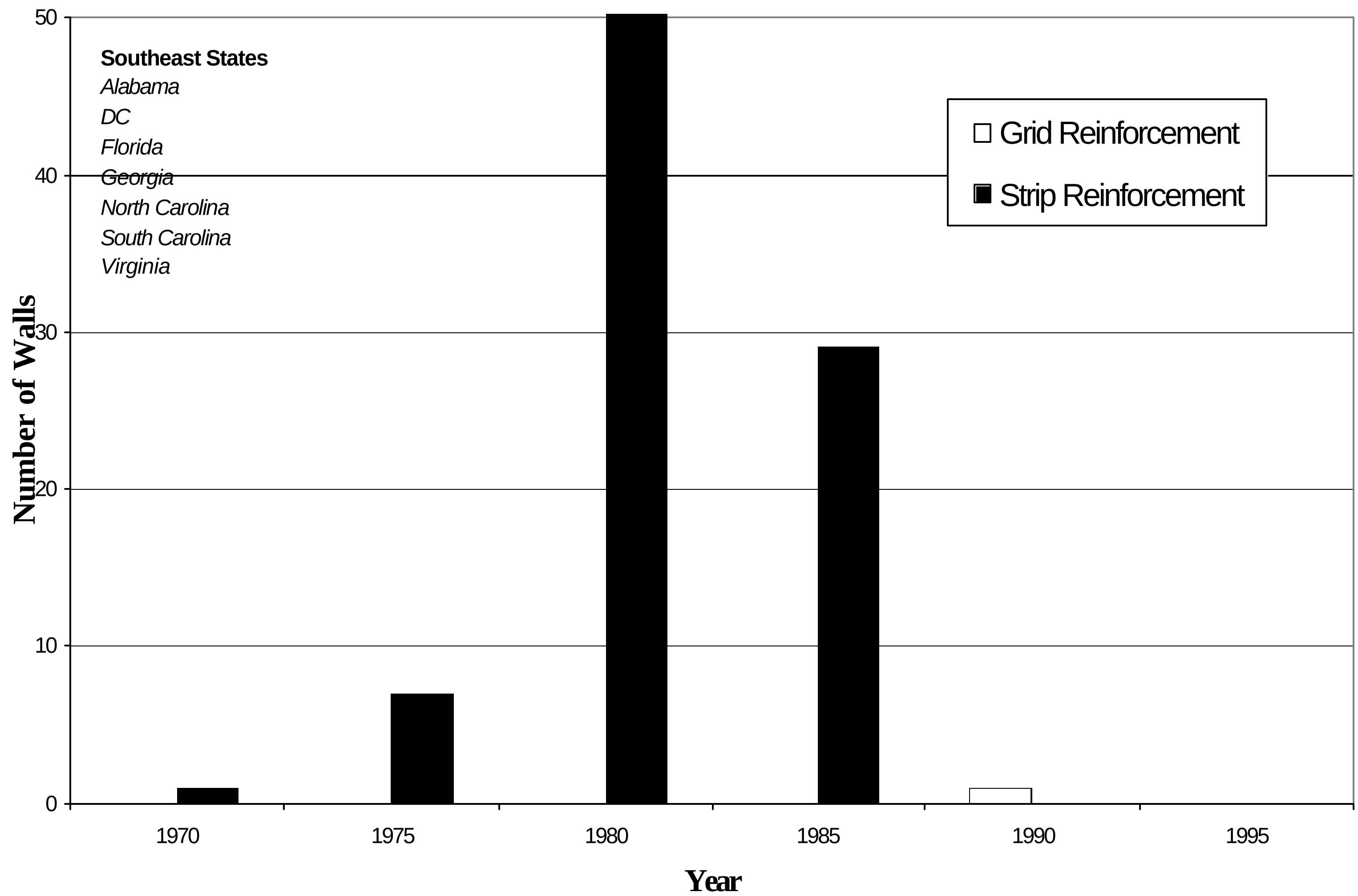
MSE Usage in the Northeast Region of the United States



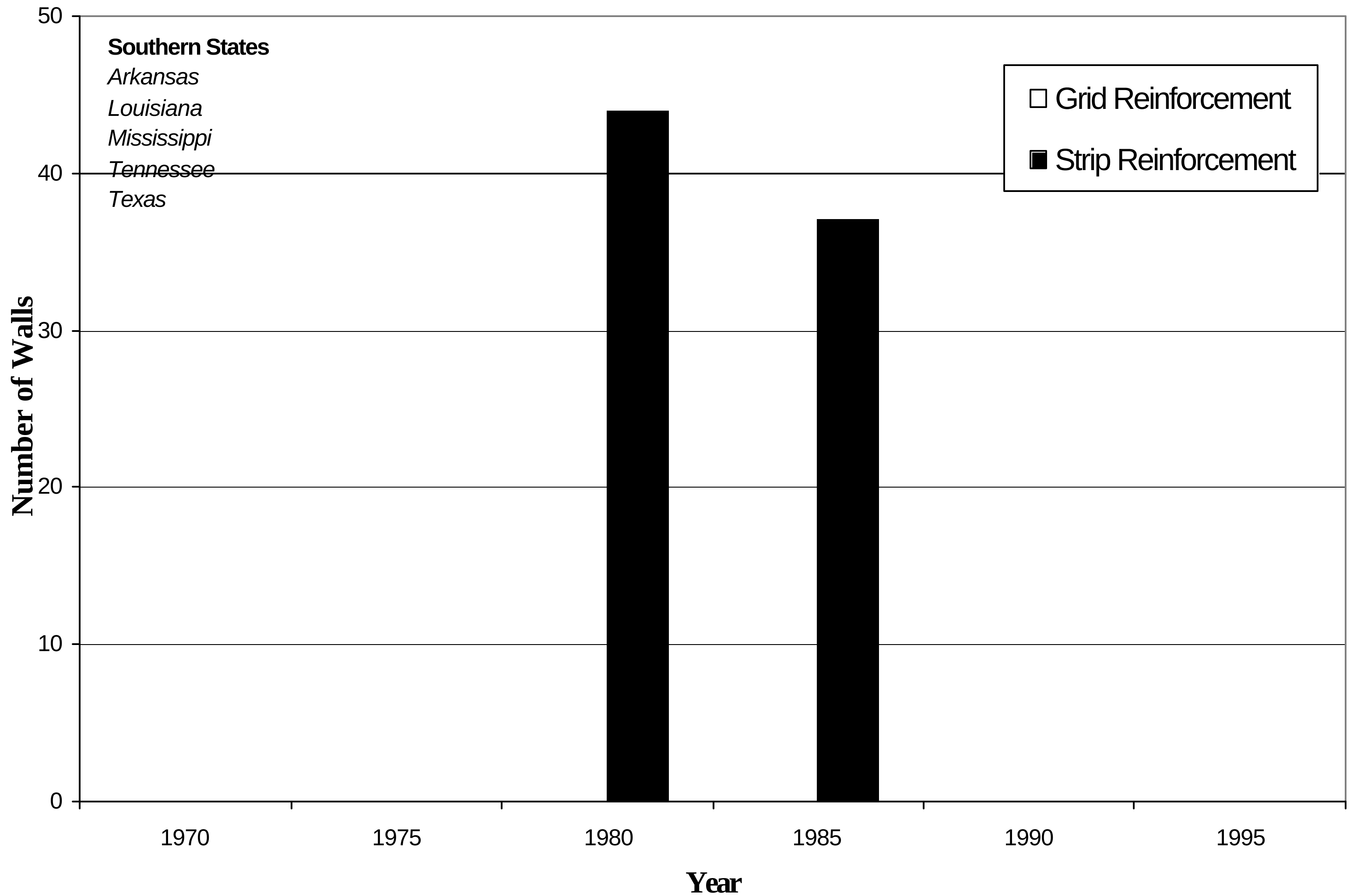
MSE Usage in the High Plains Region of the United States



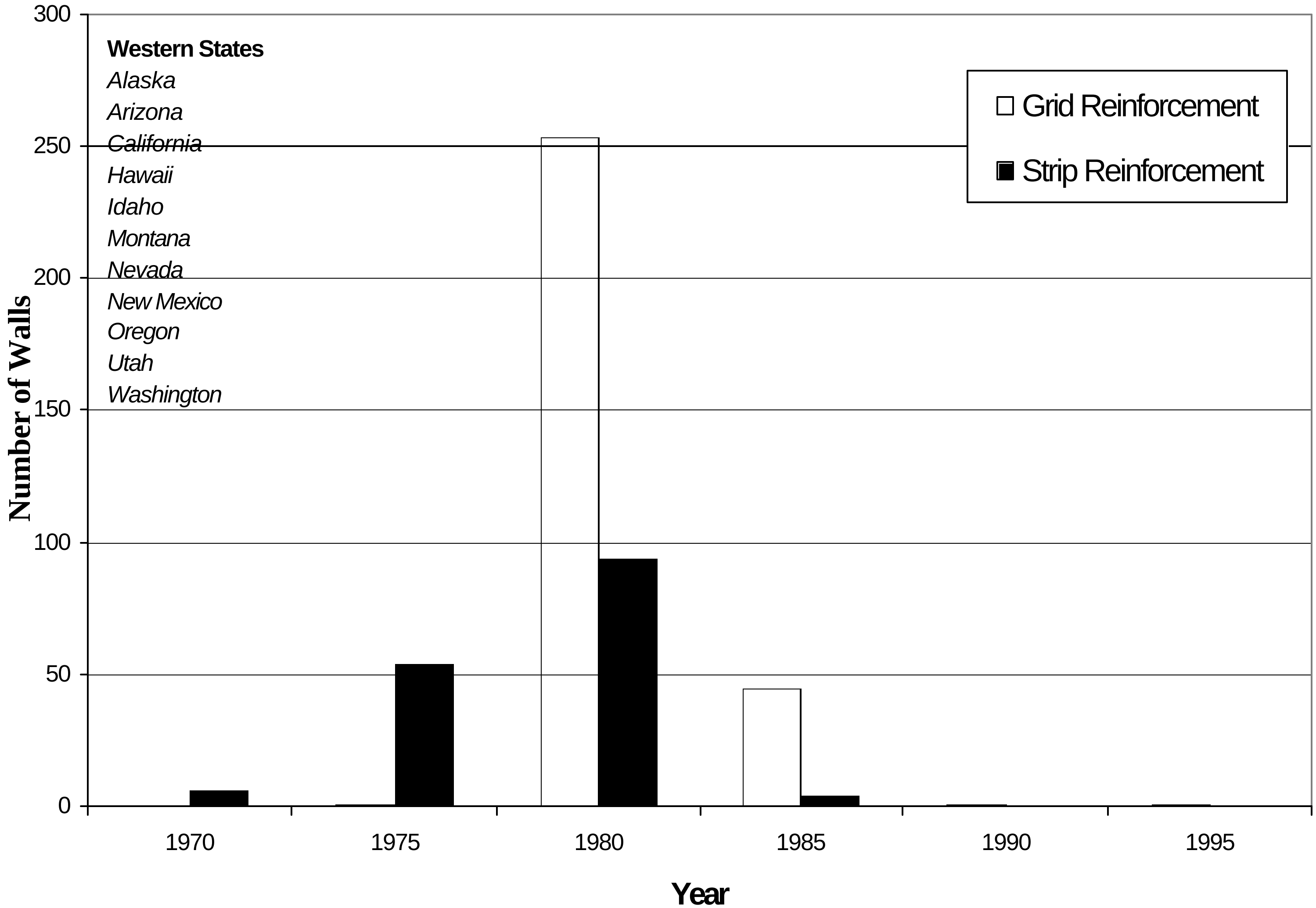
MSE Usage in the Midwest Region of the United States



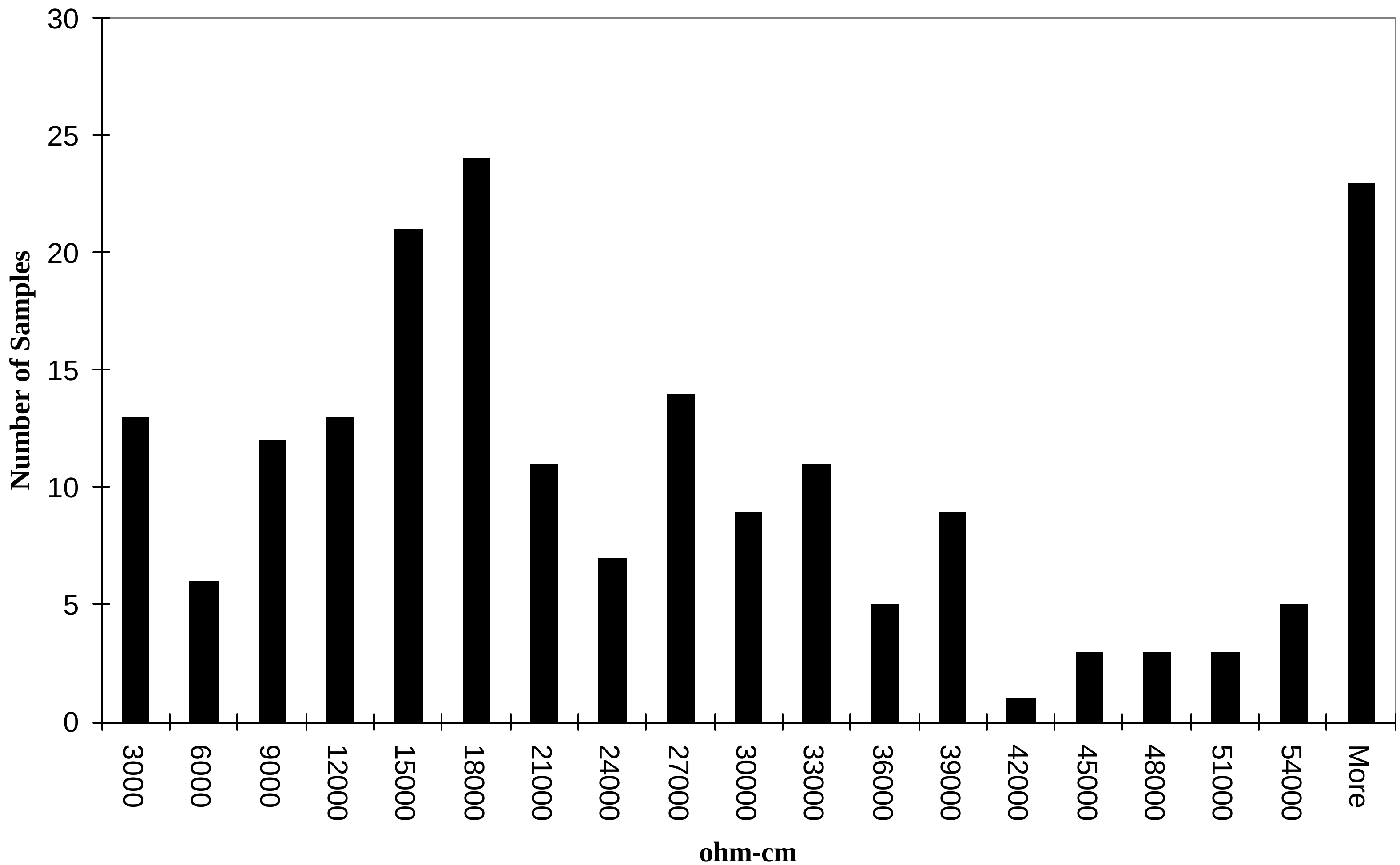
MSE Usage in the Southeast Region of the United States



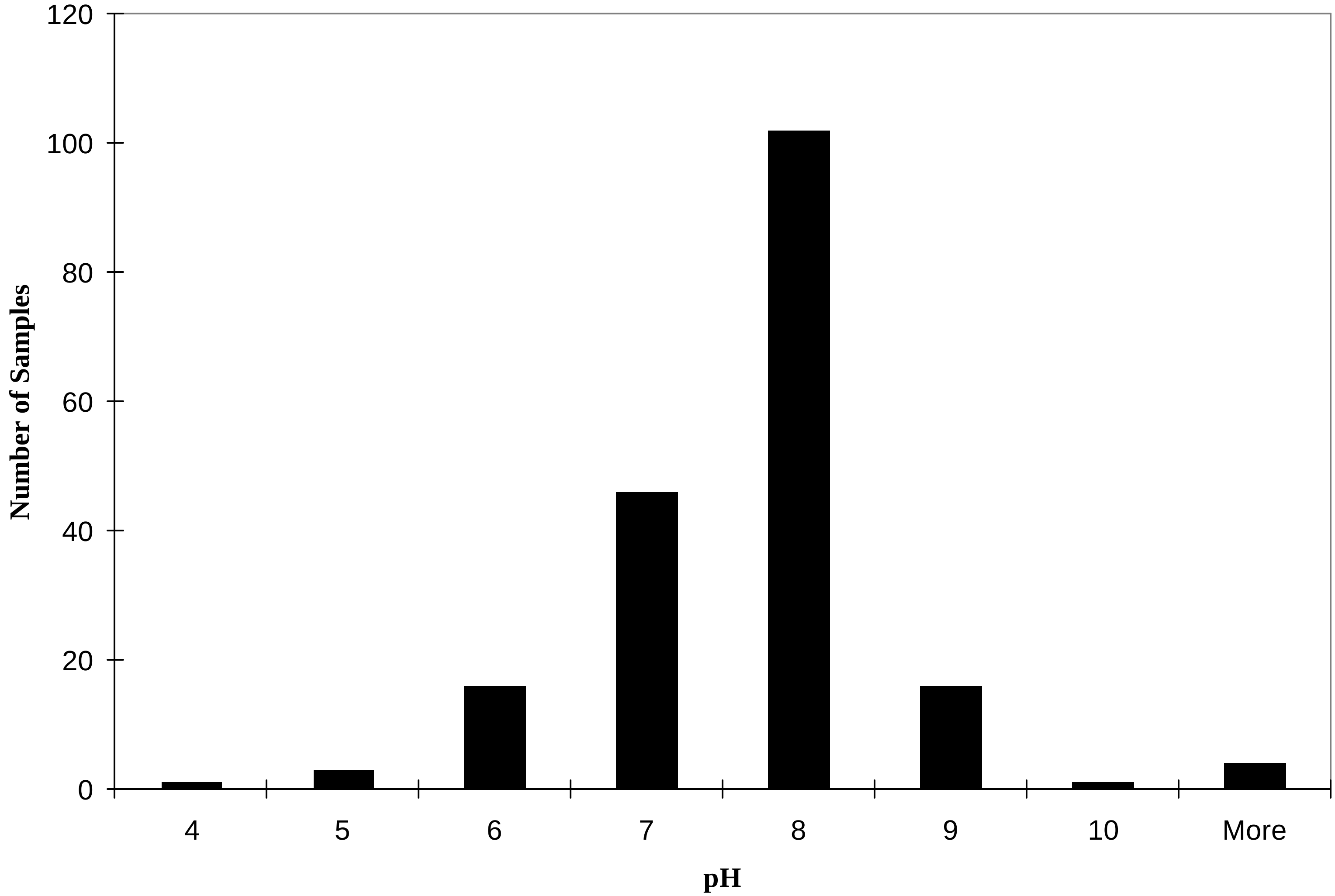
MSE Usage in the Southern Region of the United States



MSE Usage in the Western Region of the United States



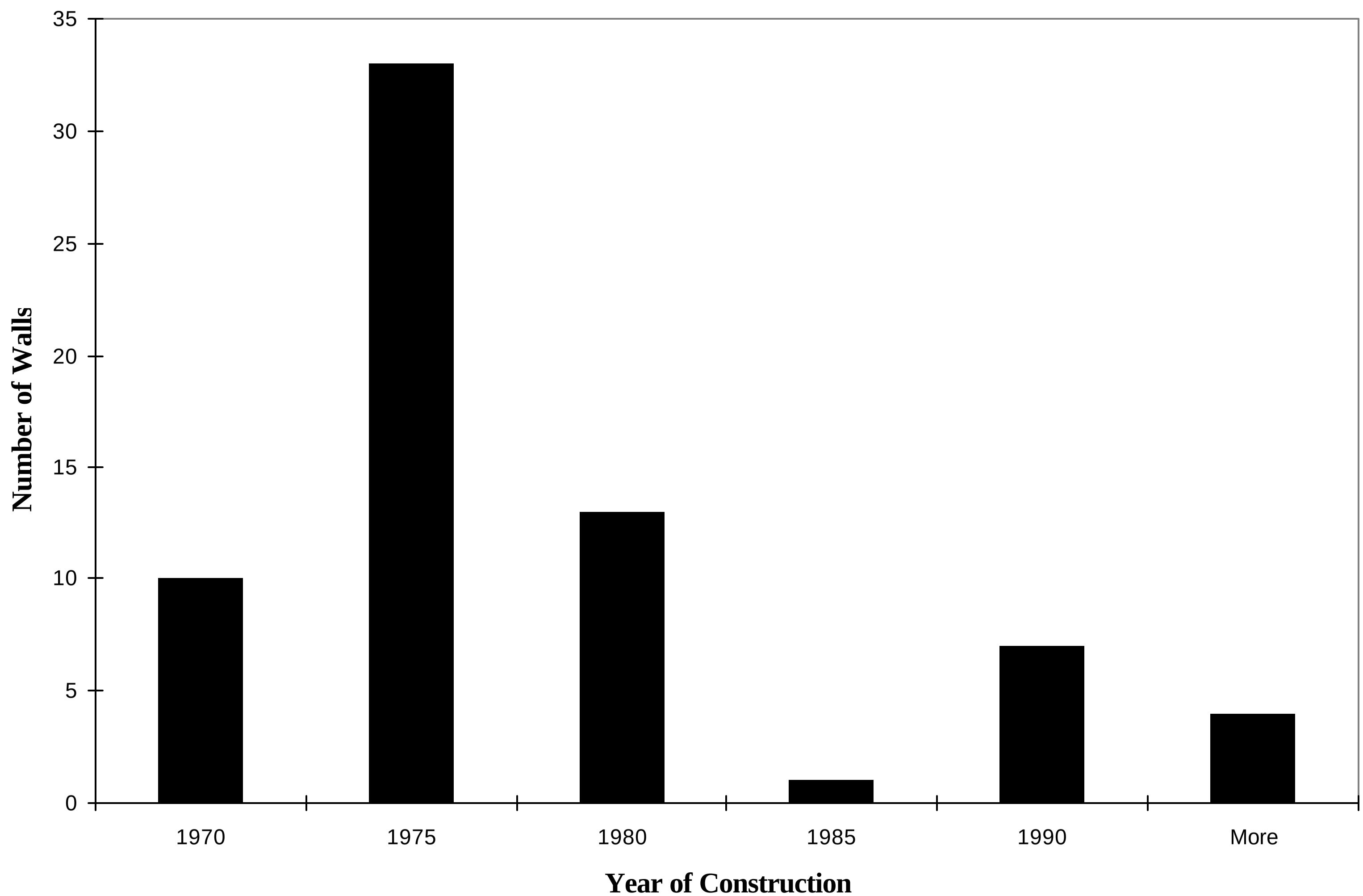
Distribution of Resistivity Measurements for MSE Backfills



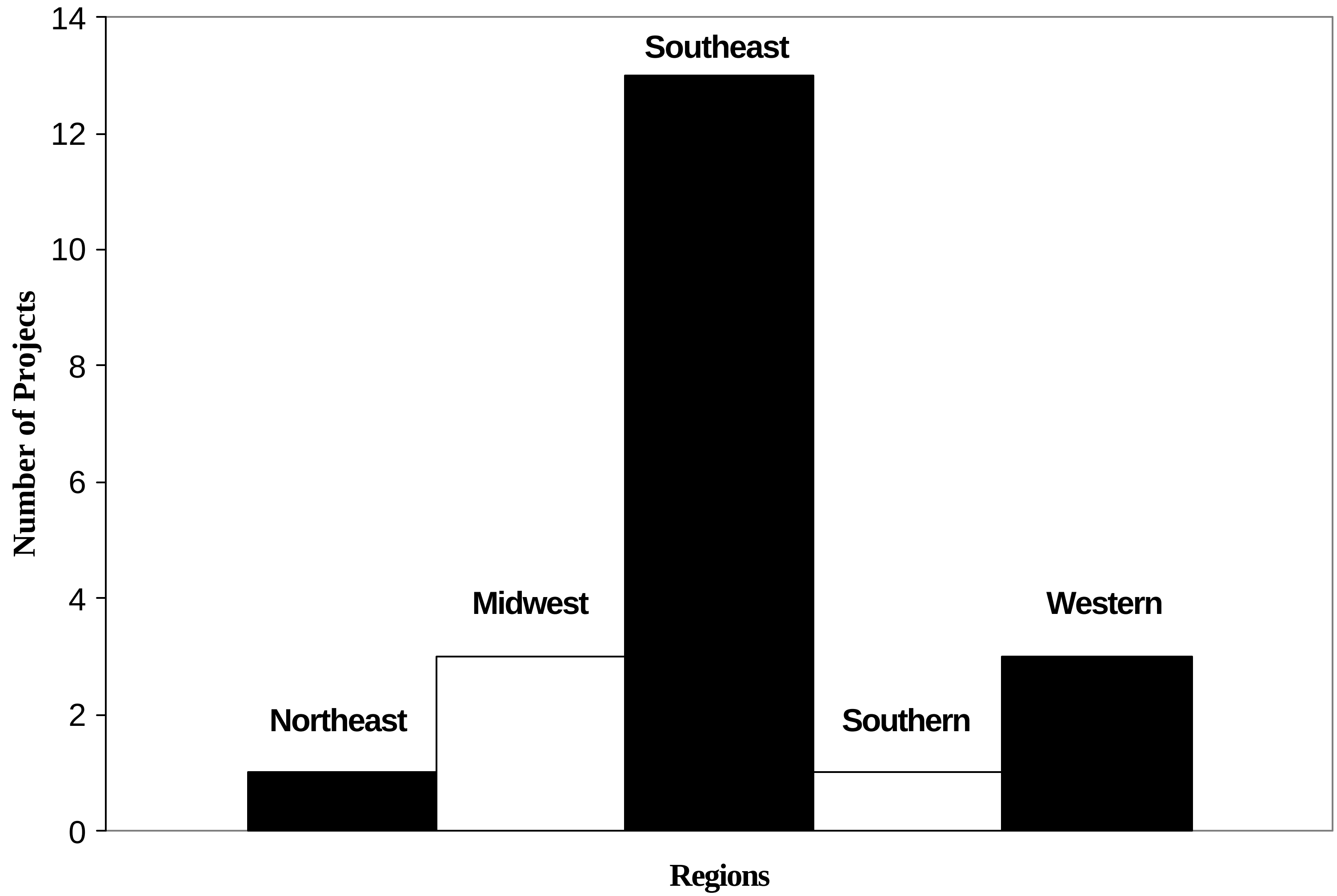
Distribution of pH Measurements for MSE Backfills.

APPENDIX C

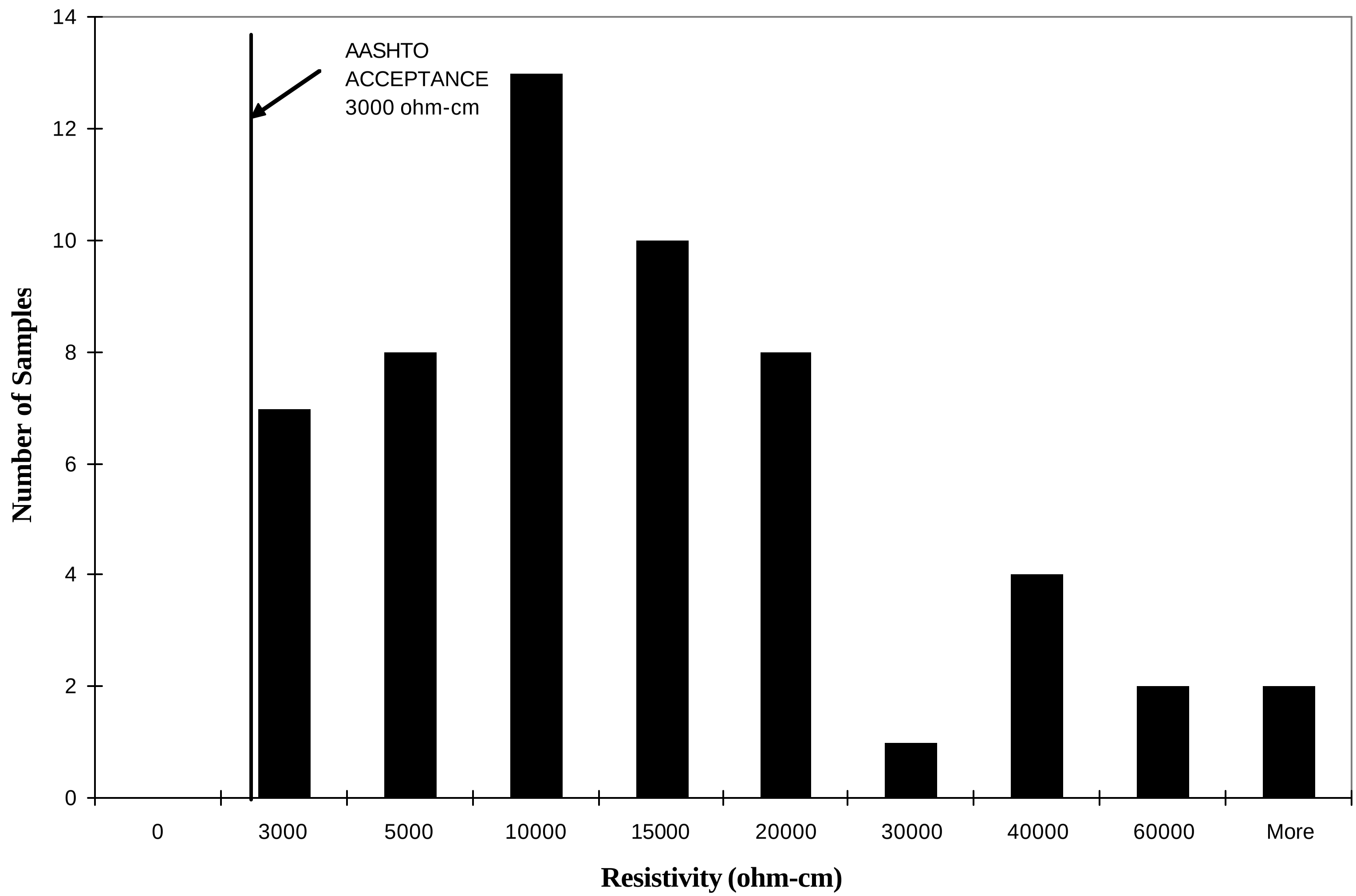
ATTRIBUTES OF MSE WALLS
WITH
METAL LOSS MONITORING DATA



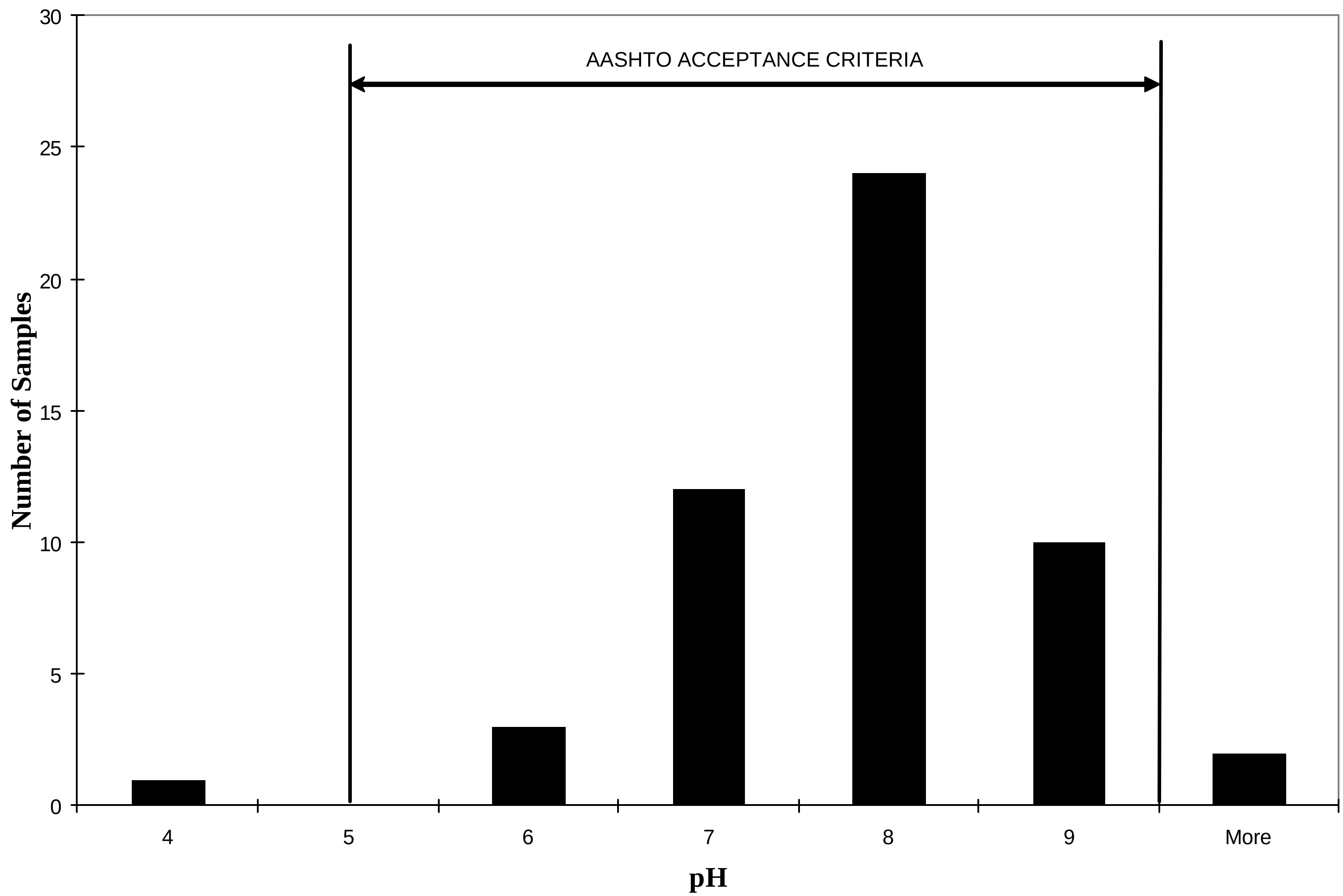
Age of Reinforcements for MSE Walls with Metal Loss Monitoring Data.



Locations by Region for MSE Walls with Corrosion Monitoring Data.



Measurements of Backfill Resistivity for MSE Walls with Metal Loss Monitoring Data.



Measurements of Backfill pH for MSE Walls with Metal Loss Monitoring Data.