State of the Practice of MSE Wall Design for Highway Structures

Peter L. Anderson, P.E., M.ASCE1, Robert A. Gladstone, P.E., M.ASCE2, John E. Sankey, P.E., M.ASCE3

1The Reinforced Earth Company, 133 Park Street, North Reading, MA 01864; PH (978) 664-2830; FAX (978) 664-2831; Email: panderson@reinforcedearth.com

2Association for Metallically Stabilized Earth, P.O. Box 9142, McLean, VA 22102; PH (703) 749-3033; FAX (703) 749-3034; Email: bobgladstone@amsewalls.org

3The Reinforced Earth Company, 8614 Westwood Center Drive, Vienna, VA 22182; PH (703) 821-1175; FAX (703) 821-1815; Email: jsankey@reinforcedearth.com

ABSTRACT

The state of the practice of MSE wall design has become more complex as more and more systems, engineers and researchers have become involved in the practice. There are correct ways to design MSE walls, to apply traffic surcharge, to select design parameters and backfill, to assess service life, to address special design conditions such as bridge abutments, traffic barriers and earthquakes, and to select the wall design method itself. Yet the complexity persists, arising from policy changes and a multitude of design choices. This paper will discuss these and other areas of confusion and provide clarification regarding accepted, reliable methods of MSE design that have been proven in the field for more than forty years.

INTRODUCTION

At the invitation of the Federal Highway Administration (FHWA), Reinforced Earth® structures with their inextensible (steel) reinforcements were introduced in the United States in 1971. This new technology was quickly successful, both structurally and economically, giving rise to competing systems, a new industry and the generic name Mechanically Stabilized Earth (MSE). Design of MSE walls with inextensible reinforcements was, and still is, performed by assuming the MSE structure behaves as a rigid body, sizing it to resist external loads applied by the retained soil and by any surcharge, then verifying internal stability by checking reinforcement pullout and tensile rupture. This design method, derived from basic soil mechanics, is known as the Coherent Gravity Method (Anderson et al., 2010). In the 1970s, the Coherent Gravity Method was refined by several MSE-specific research studies to include a bilinear envelope of maximum reinforcement tension and a variable state of stress.
based on depth within the structure. From extensive usage, reinforcement pullout resistance parameters were developed for both ribbed reinforcing strips and welded wire mesh reinforcement and the behavior of steel-reinforced MSE structures became well understood and accepted.

The development of extensible (geosynthetic) reinforcements, in the late 1970s, necessitated use of the Tieback Wedge design method to account for differences in both internal stress distribution and deformation characteristics evident in MSE structures reinforced with extensible reinforcements. Confusion arose among engineers due to differences between the two design methods, giving rise to even more design methods, some of which were intended to work for both inextensible and extensible reinforcements. Meanwhile, the validity of the Coherent Gravity Method was being proven in tens of thousands of highway structures and it became the MSE structure design method either accepted or required by the majority of state departments of transportation (DOTs).

In 1975 the Federal Highway Administration promulgated its "Standard Specifications for Reinforced Earth Walls", later renamed for MSE walls, but this specification was abandoned in the early 1990s when the American Association of State Highway and Transportation Officials (AASHTO) created its specification of similar title. Although FHWA and AASHTO generally agree, they differ on some points, as seen by comparing training materials created by the FHWA's National Highway Institute (NHI, 2009) with design requirements in the AASHTO specifications.

In addition to differences between NHI and AASHTO, MSE designers have also had to deal with a transition from U.S. customary units to metric units and then back to U.S. units, as well as a mandated transition from Allowable Stress Design (ASD) to Load and Resistance Factor Design (LRFD). Today, MSE walls for highways are designed using the Coherent Gravity, the Simplified, and occasionally other methods, and according to numerous DOT specifications. There are still ASD and metric-unit designs ongoing for projects developed years ago, creating challenges for MSE wall designers and reviewers.

The practice of MSE wall design was once straightforward; today it can be confusing and complex. The following recommendations will help to minimize confusion and complexity:

- Continued and exclusive use of AASHTO specifications for MSE wall design,
- NHI courses should teach material consistent with AASHTO specifications,
This paper presents the state of the practice of MSE wall design for highway structures by discussing key aspects of MSE design and performance, the different reinforcement materials, and the reasons a different design method should be used for each reinforcement material.

**DESIGN PLATFORM AND UNITS (LRFD vs. ASD)**

The practice of MSE wall design is in an FHWA-mandated transition from Allowable Stress Design (ASD) to Load and Resistance Factor Design (LRFD). While some DOTs began implementing LRFD for MSE walls before the mandate, others still have not made that transition. Another transition is working through the backlog of projects designed in metric units. Taken together, these transitions require engineers to have daily familiarity with two design platforms (ASD, LRFD), two sets of units (metric, U.S.), multiple MSE design methods, and multiple state specifications.

**DESIGN RESPONSIBILITY**

Most DOTs are clear on who is responsible for each aspect of the design of MSE walls. The distribution of design responsibility is as follows:

**External Stability.** The owner (DOT), or the owner's geotechnical consultant, is responsible for the external stability of the proposed structure. The logic is simple: the owner is proposing to build the structure in the specified location and it is the owner's responsibility to investigate the feasibility of the proposed improvement, including the adequacy of the foundation soils to support the proposed structure. External stability analysis includes global stability of the structure, bearing capacity analysis of the foundation soils, and settlement analysis of the proposed structure.

An external stability analysis of an MSE structure is straightforward for a qualified geotechnical engineer and can follow the typical steps outlined below.

1. The foundation width for an MSE structure is taken equal to the soil reinforcement length, which is typically 0.7 times the height of the structure.
2. The height of the structure is taken from the top of leveling pad to the finished grade at the top of wall.
3. The reinforced soil mass may be modeled as a block, using a high cohesion value to force the failure surfaces being examined to be external to the structure. For example, design properties of $\gamma = 20$ kN/m$^3$, $\phi = 34^\circ$ and $c = 70$ kN/m$^2$ may be used to model the reinforced soil mass in a global stability analysis.
4. The applied bearing pressure at the base of an MSE structure is approximately 135% of the overburden weight of soil and surcharge.
5. Factors of safety of 1.3 against global instability and 2.0 against bearing capacity failure are adequate for MSE walls (Anderson, 1991).
6. Settlement analysis is conducted by treating the MSE structure as a continuous strip footing of width equal to the strip length, with the applied bearing pressure as estimated in step 4.

7. Settlement at the wall face is approximately one-half of the value calculated in step 6.

8. MSE structures constructed with precast concrete facing panels (1.5 m x 1.5 m and 1.5 m x 3.0 m) and 20 mm thick bearing pads in the panel joints can tolerate large total settlements up to 300 mm, with up to 1% differential settlement (i.e., 300 mm in 30 m) without showing signs of distress in the wall facing.

**Internal Stability.** The MSE wall system supplier is responsible for internal stability design, including checking both pullout and rupture of the reinforcements. The supplier is also responsible for design of all wall system components, including the facing units, soil reinforcements, soil reinforcement connections to the facing units, bearing pads and joint-covering filter fabric. Wall suppliers also provide calculations that check sliding and overturning of the MSE gravity mass and determine the eccentricity of the structure and the applied bearing pressure at the base of the structure.

The state of the practice of MSE wall design is substantially about internal stability. Therefore, the following discussion reviews many aspects of internal stability design. It is useful to start at the beginning, by reviewing the basic mechanics of MSE structures.

**BASIC MECHANICS OF MECHANICALLY STABILIZED EARTH**

As explained by McKittrick (1978),

"The basic mechanics of Reinforced Earth were well understood by Vidal and were explained in detail in his early publications. A simplification of these basic mechanics can be illustrated by Figure 1. As shown in Figure 1a, an axial load on a sample of granular material will result in lateral expansion in dense materials. Because of dilation, the lateral strain is more than one-half the axial strain. However, if inextensible horizontal reinforcing elements are placed within the soil mass, as shown in Figure 1b, these reinforcements will prevent lateral strain because of friction between the reinforcing elements and the soil, and the behavior will be as if a lateral restraining force or load had been imposed on the element. This equivalent lateral load on the soil element is equal to the earth pressure at rest (K₀σᵥ). Each element of the soil mass is acted upon by a lateral stress equal K₀σᵥ. Therefore, as the vertical stresses increase, the horizontal restraining stresses or lateral forces also increase in direct proportion."
Mechanically Stabilized Earth reinforced with inextensible (steel) reinforcements is, therefore, a composite material, combining the compressive and shear strengths of compacted granular fill with the tensile strength of horizontal, inextensible reinforcements.

A practical interpretation of McKittrick's explanation is that the larger the surcharge applied to an MSE structure, the stronger the composite MSE material becomes. Understanding this basic soil mechanics fact about MSE is crucial to the correct use of this composite construction material. With the addition of a facing system, MSE structures are well suited for use as retaining walls, bridge abutments and other, even more heavily loaded structures.

TRAFFIC SURCHARGE – To Apply or Not To Apply?

The design of MSE structures has moved from ASD, where many designers have developed an intuitive "feel" for the behavior of structures and the safety factors associated with their design, to LRFD, which uses non-intuitive factors derived through statistical analysis of past behavior. Statistical analysis can offer valuable insights. However, in the design of MSE structures, the resulting loss of intuition has led to a breakdown of logic regarding structure behavior when carrying a traffic surcharge. Therefore, it is worth repeating the fundamental concept of soil mechanics, stated above by McKittrick, that "... as the vertical stresses [on a sample of granular material] increase, the horizontal restraining stresses or lateral forces also increase in direct proportion." Rephrased in the context of surcharge loads on MSE structures, the larger the surcharge one applies to an MSE structure, the stronger the MSE structure becomes.
The AASHTO Specifications addressed this fundamental concept by a revision proposed in 2008 and issued in the 2009 Interim Specifications (AASHTO, 2009). AASHTO’s explanation for this change is perfectly clear:

"The application of live load surcharge with regard to pullout calculations for internal stability of MSE walls has been confusing, resulting in widely differing interpretations of the specifications regarding this issue. Based on a review of the historical development of this specification, the intent of the specification is to recommend that live load surcharge not be considered for pullout calculations. This applies to the calculation of reinforcement load (T_max) for evaluation of pullout stability, and the calculation of vertical stress for calculation of pullout resistance." (2008 AASHTO Bridge Committee Agenda Item: 42; Subject: LRFD Bridge Design Specifications, Section 11, Article 11.10.6.2.1; Technical Committee T-15 Substructures and Retaining Walls, unpublished.)

Therefore, two separate calculations of reinforcement tension (T_max) are required and engineers should be taught the following:

- When calculating T_max as part of performing reinforcement and connection rupture calculations, apply the surcharge to the MSE reinforced soil.
- When calculating T_max as part of performing pullout calculations, do not apply the surcharge to the MSE reinforced soil.

GRANULAR BACKFILL FOR MSE WALLS

The backfill used in MSE structures is critical to their overall performance. To meet performance requirements, MSE structure backfill is specified by AASHTO as granular material with a 100 mm maximum size and less than 15% fines (Table 1).

<table>
<thead>
<tr>
<th>U.S. Sieve Size</th>
<th>Percent Passing</th>
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<tbody>
<tr>
<td>100 mm</td>
<td>100</td>
</tr>
<tr>
<td>420 μm</td>
<td>0-60</td>
</tr>
<tr>
<td>75 μm</td>
<td>0-15</td>
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</tbody>
</table>

Additional requirements for plasticity index, internal friction angle, soundness and electrochemical properties are also given by AASHTO. Some DOTs vary the gradation limits or reduce the allowable fines content based on local material characteristics.
DESIGN PARAMETERS

Typically the design of an MSE structure is completed using assumed design parameters. The design is typically submitted, reviewed and approved before the contractor obtains approval of the select backfill that will be used to construct the MSE walls. The most common assumed design parameters are shown in Table 2.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Unit Weight</th>
<th>Friction Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Select Structure Backfill</td>
<td>20 kN/m³</td>
<td>34°</td>
</tr>
<tr>
<td>Retained Fill</td>
<td>20 kN/m³</td>
<td>30°</td>
</tr>
<tr>
<td>Foundation Soils</td>
<td>-----</td>
<td>30°</td>
</tr>
</tbody>
</table>

A 34° friction angle (ϕ) is typically assumed for the select backfill, as this is the maximum value permitted by the AASHTO specifications unless project-specific test data is provided. Use of this friction angle is a good choice for design of MSE walls because 34° is approximately the shear strength that will mobilize in the structure for most granular soils meeting the gradation requirements.

The actual material used to construct the structure will likely have somewhat different parameters. The unit weight may be higher or lower and the measured peak shear strength will likely be higher, often considerably higher than 34°. This is acceptable, since one of the purposes of using safety factors (or load and resistance factors) is to account for the uncertainties in the backfill properties. Use of peak shear strength in the design of structures should be avoided because peak shear strength is an intrinsic property that only develops if there is sufficient soil strain. Such strain is prevented by the soil reinforcements.

The mobilized shear strength that develops within a structure develops at strains less than those required to develop the peak shear strength. If too much deformation is allowed to occur, as may be the case if the design is based on peak shear strength, the shear strength of the soil will reduce to its residual value. The residual shear strength is likely much closer to 34° than it is to the peak shear strength. Therefore, use of 34° for design is a prudent choice, one that has been assumed in design and proven through four decades of MSE structure performance.

SERVICE LIFE

The service life of an MSE structure is defined as the period of time during which

- In terms of ASD, the tensile stress in the soil reinforcements is less than or equal to the allowable stress for the steel or,
- In terms of LRFD, the factored tensile resistance of the soil reinforcements is greater than or equal to the factored tensile load.
MSE retaining walls are routinely designed for a 75-year service life; those supporting bridges are typically designed for 100 years. The primary factor affecting the service life of an MSE structure is the long term durability of the reinforcements which, for inextensible (steel) reinforcement materials, is closely related to backfill electrochemical properties.

Research on buried galvanized steel, conducted by the National Bureau of Standards, Terre Armee Internationale (TAI), FHWA, and several state DOTs, confirms that the metal loss rates used in the design of MSE structures (Table 3) are conservative for steel soil reinforcements galvanized with 86 μm of zinc and buried in backfill meeting the electrochemical requirements shown in Table 4 (AMSE, 2006; Gladstone, et al., 2006). These loss rates and backfill electrochemical requirements have been codified in the AASHTO specifications (AASHTO, 2002; AASHTO, 2010).

<table>
<thead>
<tr>
<th>Table 3. Metal Loss Rates</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Zinc (first 2 years)</td>
</tr>
<tr>
<td>Zinc (subsequent years to depletion)</td>
</tr>
<tr>
<td>Carbon steel (after zinc depletion)</td>
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<table>
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<tr>
<th>Table 4. Electrochemical Requirements</th>
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<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>Resistivity</td>
</tr>
<tr>
<td>pH</td>
</tr>
<tr>
<td>Chlorides</td>
</tr>
<tr>
<td>Sulfates</td>
</tr>
</tbody>
</table>

The carbon steel loss rate in Table 3 is proportional to the loss of tensile strength for the sizes of strips and wires typically used as soil reinforcements in MSE structures. The minimum sizes of strips and wires that will assure validity of the metal loss model are discussed by Smith, et al. (1996). In general, according to Smith, small diameter wires (smaller than W10 for a 100 year service life and W7 for a 75 year service life) should not be used as the primary tensile members without additional data being developed on their long term tensile strength.

The loss rates in Table 3 determine the sacrificial thickness of steel that must be added to the load-carrying cross section to produce the design cross section. At the end of the service life, after 75 or 100 years of metal loss, the remaining steel will have a factor of safety of 1.8 against yield. In terms of LRFD, at the end of the service life the factored tensile resistance will be greater than or equal to the factored reinforcement tensile load.
DESIGN METHODS

Not surprisingly, MSE wall designers can become confused by the choices they must make. The two types of MSE wall reinforcements, inextensible (steel) and extensible (geosynthetic), behave differently. To obtain the required structure performance and service life, designers must understand reinforcement behavior and use the design method appropriate to each reinforcement type. The paragraphs below discuss design methods and reinforcement behaviors, match the design method to the reinforcement, and clearly show that the Coherent Gravity Method should be used for design of MSE walls with inextensible reinforcements and the Simplified Method should be used for MSE walls with extensible reinforcements. This is the state of the practice, with proper selection of the MSE design method being critical to successful design of MSE walls for highway structures.

Coherent Gravity Method. The Coherent Gravity Method was developed by postulating MSE structure behavior, observing actual structures, and interpreting observations in terms of the fundamentals of statics and soil mechanics (Anderson, et al., 2010). Three international symposia on soil reinforcement in 1978 and 1979, followed by publication of "Reinforced Earth Structures, Recommendations and Rules of the Art" (French Ministry of Transport, 1979), presented a substantial body of knowledge and defined the Coherent Gravity Method for the design of MSE structures. The method includes a bilinear envelope of maximum reinforcement tension, a state of stress varying with depth within the structure, high-pullout-resistance reinforcements (originally ribbed strips, with data becoming available later for welded wire mesh reinforcements), and minimal reinforcement movement and elongation. Design characteristics of the Coherent Gravity Method, as shown in Figure 2, are listed below.

FIG. 2. Characteristics of the Coherent Gravity Method
• A rectangular cross section ("block") defined by the structure height, H, and the reinforcement length, L;
• Application of vertical and horizontal forces to the block, creating eccentric loading;
• A Meyerhof bearing pressure distribution at the base of the structure to determine foundation reactions and the repeated use of Meyerhof to determine the vertical earth pressure at each reinforcement level (Meyerhof, 1953);
• A state of stress decreasing from at rest ($K_o$) at the top of the structure to active ($K_a$) at a depth of 6 m and more;
• The resulting tensile forces in the reinforcements, determined from the horizontal earth pressure multiplied by the tributary area of the wall face restrained by the reinforcement at that level;
• The bilinear envelope of maximum reinforcement tension that separates the active from the resistive zone; and
• The inextensibility and high pullout resistance of the reinforcements which maintain the internal stability of the block.

The effects of externally applied loads on the reinforced soil mass, and the tendency of those loads to increase vertical and horizontal stresses within the structure, were confirmed by an extensive finite element study of 6 m and 10.5 m high walls (Anderson, et al., 1983). The Coherent Gravity Method was reported in its entirety, including worked example calculations, by Mitchell, et al., in NCHRP Report 290 (NCHRP, 1987).

**Tieback Wedge Method.** The Tieback Wedge Method was developed by Bell, et al. (1975) as an extension of the trial wedge method from traditional soil mechanics (Huntington, 1957), and has always been the appropriate design method for geosynthetic-reinforced MSE walls. In an MSE wall with geosynthetic reinforcements, the failure plane is assumed to develop along the Rankine rupture surface defined by a straight line oriented at an angle of $45+\phi/2$ from the horizontal and passing through the toe of the wall. Sufficient deformation is assumed to occur for an active earth pressure condition to exist from top to bottom of wall. The Rankine failure plane is not modified by inclusion of the extensible geosynthetic reinforcements. Therefore, reinforcement strain actually allows the failure plane to develop and the geosynthetic reinforcements, acting as tiebacks, restrain the active wedge from failing. This contrasts sharply with the Coherent Gravity Method, where the shape of the bilinear boundary between the active and resistive zones is based on the location of maximum reinforcement tension, the failure plane does not actually develop, the active wedge does not displace, and the inextensibility of the steel reinforcements prevents structure deformation.

**Structure Stiffness Method.** The Structure Stiffness Method was developed by Christopher, et al. (1990) based on instrumentation of full scale test walls and review of data reported in the literature from instrumented in-service walls. The Structure Stiffness Method is similar to the Tieback Wedge Method, however a bilinear envelope of maximum reinforcement tension is assumed for inextensible (steel)
reinforcements and a Rankine failure plane angled at 45° + φ/2 from the horizontal is assumed for extensible (geosynthetic) reinforcements. The lateral earth pressure coefficient, $K_r$, is based on a complex formula that takes into account the global stiffness of the reinforcement, where the global stiffness is directly related to the area of tensile reinforcement times the reinforcement modulus of elasticity. Therefore, as the reinforcement density increases, both the global stiffness and the resulting coefficient of earth pressure, $K_r$, increase. This method was not adopted by state DOTs and, therefore, does not appear in any AASHTO specifications. However, the method did lead to development of the earth pressure ratio $K_r/K_a$ which is now used in the Simplified Method.

**Simplified Method.** The Simplified Method was developed from the Tieback Wedge Method to create a single design procedure applicable to MSE walls reinforced with either inextensible or extensible reinforcements. Instead of calculating the increase in internal vertical stress due to overturning at every inextensible reinforcement level, the Simplified Method approximates this stress increase by simply adding 0.2 $\gamma z$ to the soil overburden. However, no stress increase is used with extensible reinforcements. The Simplified Method uses the Coherent Gravity Method's bilinear envelope of maximum reinforcement tension for walls reinforced with inextensible reinforcements and the Rankine failure plane, inclined at 45° + φ/2 from the horizontal, for extensible reinforcements. In general, the Simplified Method is the Tieback Wedge Method with $K_r/K_a$ ratios adopted from development of the Structure Stiffness Method.

**$K_o$-Stiffness Method.** The $K_o$-Stiffness Method, developed by Allen, et al. (2001), is yet another method intended to be applicable to the design of MSE structures with either inextensible or extensible reinforcements. Similar to the structure stiffness method, the $K_o$-stiffness Method requires use of a complex equation to calculate the peak tension in each reinforcement layer. The components of this equation include a distribution factor, a local stiffness factor, a facing batter factor, a facing stiffness factor, and a global reinforcement stiffness factor, all as modifications to the at-rest earth pressure coefficient, $K_o$. Similar to the Structure Stiffness Method, this method has not been adopted by state DOTs and, therefore, does not appear in any AASHTO specifications.

**COMPARING THE DESIGN METHODS**

This is the state of the practice. Prior to development of the Simplified Method, the Coherent Gravity Method was used for design of MSE walls reinforced with inextensible (steel) reinforcements and the Tieback Wedge Method (now the Simplified Method) was used for design of MSE walls reinforced with extensible (geosynthetic) reinforcements. Both the Coherent Gravity Method and the Simplified Method are outlined in Section 11 of the AASHTO LRFD Bridge Design Specifications (AASHTO, 2010). To select the proper design method, one must understand reinforcement properties and behavior, so the following sections explain the behavior differences between inextensible and extensible reinforcements. This
discussion clearly demonstrates why the Coherent Gravity Method should be used for design of MSE walls with inextensible reinforcements, and why the Simplified (Tieback Wedge) Method should be used for design of MSE walls with extensible reinforcements.

**Differences in Reinforcement Behavior.** Pullout tests on inextensible and extensible soil reinforcements begin the same, regardless of reinforcement type. The reinforcements are placed between layers of compacted soil in a pullout box and an overburden load is applied to the soil by an air bladder or mechanical means. The pullout force is applied to the leading end of the soil reinforcement and the pullout force and resulting displacement of the reinforcement are measured at frequent intervals. The pullout resistance of the reinforcement should be determined at a displacement of 20 mm (Christopher, et al., 1990).

The applied pullout force and resulting displacement of the reinforcement are measured simultaneously, but this is where the similarity between the reinforcement types ends. Because inextensible reinforcements experience virtually no elongation, displacement is measured at the leading end where the load is applied. For extensible reinforcements, however, displacement is measured at the trailing end, opposite from the end where the load is applied. This difference is necessary because significant elongation of the extensible reinforcement occurs, but by measuring displacement at the trailing end, deformation of the geosynthetic reinforcement is eliminated from the measurement. Recognizing this major difference in test protocol is fundamental to understanding why different design methods should be used for inextensible and extensible reinforcements.

**Inextensible (Steel) Reinforcement.** With inextensible reinforcements, the displacement at the leading end is nearly the same as the displacement at the free end because reinforcement strain is negligible. The friction developed between the reinforcement and the soil is determined for a leading edge displacement of 20 mm, and the transfer of load to the soil via friction is uniformly distributed over the full length of the reinforcement.

In an actual structure, the load is applied to the reinforcement by the soil within the active zone, which is trying to escape through the wall face. The magnitude of this earth pressure depends on the vertical stress and the coefficient of lateral earth pressure. Vertical stress is a function of the overburden pressure, which increases with depth in the structure, while the coefficient of lateral earth pressure varies from at rest (K₀) at the top of the structure to active (Kₐ) at a depth of 6 m and deeper. The horizontal earth pressure becomes tension in the reinforcements through the mechanism of friction.

The tension in the reinforcement is greatest at the line of maximum tension (Figure 3), and decreases gradually over the full reinforcement length until near the free end, where the tension decreases rapidly to zero. Significant tension is observed over the full length of the reinforcements.
Figure 4 is plotted from a full-scale test structure and the matching Finite Element Model (FEM) (Bastick, et al., 1993) and shows the maximum measured reinforcement tension, the maximum tension calculated by FEM, and the tension calculated by the Coherent Gravity method. Note that all are in close agreement, and that all three clearly show the overturning effect as curvature of the line near the bottom of structure. In the United States we use the $\beta = 0$ line to represent that the lateral earth pressure acts on the mass horizontally, not at an angle of inclination. This is the more conservative design line.

As was shown in Figure 3, the tension is distributed over nearly the entire reinforcement length. The compressive strength and shear strength of the soil combine to make the MSE structure behave as a rigid body. This rigid body behavior is also evident in Figure 4, in the magnitude of the maximum reinforcement tension, which increases toward the bottom of the wall. The increase is magnified by the overturning effect of the externally applied loads. This overturning effect, determined by the Meyerhof (1953) calculation, is considered by the Coherent Gravity Method but is not considered by the Simplified Method.

**Extensible (Geosynthetic) Reinforcement.** When performing pullout testing on extensible (geosynthetic) reinforcement, displacement must be measured at the trailing end of the reinforcement, not the end at which the load is applied. This is because extensible reinforcement undergoes significant strain under load, meaning when the leading edge has displaced 20 mm, the trailing end typically will not have displaced at all. Until trailing end displacement equals 20 mm, the length over which shear stresses have developed is unknown and load transfer from the soil to the reinforcement cannot be calculated over the full reinforcement length.
Terre Armee Internationale studied the difference in pullout resistance between inextensible and extensible reinforcements (Segrestin, et al., 1996). In this study, 40 mm wide ribbed steel strips and 100 mm wide polyester straps, in 6 m and 8 m lengths, were tested and compared in pullout. The steel strips are inextensible; the geosynthetic straps, though extensible, are among the least extensible geosynthetic soil reinforcements available. Figure 5 and Figure 6 show Segrestin's results for the 6 m long reinforcements; results for the 8 m long reinforcements were similar.

Figure 5 shows that, for a 40 mm leading edge displacement (δ), the trailing end of the inextensible (steel strip) reinforcement displaced 38 mm while the trailing end of the polyester strap had zero displacement. In addition, the displacement of the polyester strap at its mid-point was only 1.6 mm, indicating that virtually no load was induced on the back 3 m of this 6 m long reinforcement. Figure 6 shows the tensile load developed in the reinforcements during the pullout test. Note that when the leading edge of both reinforcements had displaced 40 mm ("δi = 40 mm"), the tensile load in the steel reinforcement was 38.4 kN, compared to the 22.5 kN load measured in the polyester reinforcement. The inextensible reinforcement carried 170 percent of the load with only 2.5 percent as much elongation as the extensible reinforcement.

FIG. 5. Reinforcement Displacement

![Figure 5. Reinforcement Displacement](image)

FIG. 6. Reinforcement Load

![Figure 6. Reinforcement Load](image)

Taken together, Figures 5 and 6 show clearly that inextensible (steel) reinforcements work along their entire length. The friction which is mobilized along the inextensible reinforcement is uniform, but less than the limiting shear stress of the soil. The safety factor against pullout is due to the extra shear stress which can be mobilized along the full length of the reinforcement. Conversely, extensible (geosynthetic) reinforcements make use of only the minimum adherence length necessary to transfer the load to the soil. The friction which is mobilized along this length is equal to the limiting shear stress of the soil. The extra reinforcement length, which remains available but is not mobilized, provides the safety factor in pullout.
Due to the extensibility of geosynthetic soil reinforcements, the reinforcement will deflect at the failure plane as shown in Figure 7. Tension in the reinforcement will be greatest along the failure plane and will decrease rapidly behind the failure plane, based on the limiting shear stress of the soil (Figure 8, Carrubba, et al., 1999). As was seen in Figure 6 and confirmed in Figure 8, pullout tests indicate the tension in extensible reinforcements may reduce to zero a short distance beyond the failure plane, depending on soil-reinforcement friction and reinforcement extensibility.

This analysis shows that extensible reinforcements, including polyester straps, are not mobilized over their full length, and confirms what was found from the monitoring of actual structures reinforced with geosynthetic soil reinforcements (Simac, et al., 1990; Carrubba, et al., 1999) and from finite element studies (Ho, et al., 1993), especially at the bottom of structures. These observations mean that MSE structures reinforced with extensible (geosynthetic) reinforcements do not behave as rigid bodies (coherent gravity structures), while MSE structures with inextensible (steel) reinforcements do behave as coherent gravity structures.

IDENTIFY THE CORRECT DESIGN METHOD TO USE

In the current state of the practice of MSE wall design for highway structures, the AASHTO specifications include two design methods and two reinforcement types. Selecting the proper reinforcement system, then correctly applying the appropriate design method, is critical to achieving good structure performance and service life. The following statements summarize this thought process:
Coherent Gravity for Inextensible (Steel) Reinforcements. Inextensible (steel) MSE reinforcements are under tension over their full length, forming a coherent gravity mass. The measured reinforcement tensions clearly indicate an overturning effect consistent with Meyerhof (1953). The Coherent Gravity Method includes this overturning effect and predicts the measured tensions reasonably well. Therefore, the Coherent Gravity Method should be used for design of MSE walls reinforced with inextensible (steel) reinforcements.

Simplified (Tieback Wedge) for Extensible (Geosynthetic) Reinforcements. Extensible (geosynthetic) reinforcements are not under tension over their full length so an extensibly-reinforced MSE structure is not a coherent gravity mass. The Tieback Wedge Method is an accepted method for design of structures reinforced with extensible reinforcements and the Simplified Method is an MSE-specific version of the Tieback Wedge Method. Therefore, the Simplified Method should be used for design of MSE walls with extensible (geosynthetic) reinforcements.

SEISMIC DESIGN – AASHTO’s New No-Analysis Provision

At the 2011 meeting of the AASHTO Subcommittee on Bridges and Structures, state and federal bridge engineers agreed that seismic analysis is not required for MSE walls which are \( \leq 9.1 \, \text{m} \) high and subject to a design acceleration \( \leq 0.4g \). For taller walls, and for walls potentially subject to higher accelerations, seismic design in accordance with established (AASHTO) methods will still be required. This change in the state of the practice exempts most highway structures from requiring a seismic design.

TRAFFIC BARRIER DESIGN – Confirmation of TAI Loads, NHI Recommends Higher Loads

Concrete safety barriers have been constructed on MSE walls in the United States since the early 1980s. Wall-mounted barriers were developed in France and crash tested in 1982 by Terre Armée Internationale (TAI, 1982). Hundreds of miles of both cast-in-place and precast barriers are in service and performing successfully throughout the United States and around the world. The typical cross section consists of the project-specific barrier shape and a nominally horizontal moment slab (Figure 9).
Safety barriers and their supporting MSE walls are designed using a pseudo-static design method developed nearly 30 years ago (Anderson, et al., 2008; TAI, 1982). The barrier and MSE wall are designed for an impact load of 45 kN, distributed over 1.5 m of wall for checking reinforcement tension and distributed over 6 m of wall for checking soil reinforcement pullout. For reinforcement pullout to occur, at least a 6 m length of both wall and barrier would need to move out as a unit. Figure 9 shows a typical precast concrete barrier and moment slab designed by the pseudo-static design method. This or similar barrier designs have been constructed atop thousands of MSE retaining walls since 1985. Their performance has been excellent.

Since 1994, the AASHTO Specifications for the design of MSE walls has included the pseudo-static design method discussed above.

The National Cooperative Highway Research Program (NCHRP) Project 22-20, *Design of Roadside Barrier Systems Placed on MSE Retaining Walls*, was begun in July 2004 with the goal of developing standardized procedures for MSE wall barrier design. The final report (same title, published as NCHRP Report 663) (NCHRP 2011), confirmed the validity of the TAI pseudo-static design load used since 1982 to size traffic barriers and design MSE walls subject to vehicular impact. Although the NCHRP research shows that the design method and the pseudo-static load specified by AASHTO are valid, NHI uses a significantly larger design load to check pullout of the top reinforcement layer. This unexplained difference is causing considerable confusion for DOTs, which are now uncertain whether to use the NCHRP crash test-validated load or the NHI-recommended load.

**STRUCTURES SUPPORTING ABUTMENTS**

The first Reinforced Earth bridge abutments were constructed in France in 1969 and in the United States in 1974. These MSE structures were "true" abutments where the bridge beams rested on a spread footing beam seat bearing directly on the reinforced backfill (Figure 10). Mixed abutments, with piles supporting the beam seat (Figure 11), were developed later. One of the first true abutments in France carried a remarkable 76 m span; spans up to 72 m have been constructed in the U.S.

After a long period of building only a few dozen MSE abutments per year, usage has increased rapidly since the late 1990s, as owners and engineers have become more familiar with and have developed greater confidence in this technology. Approximately 600 MSE abutments (300 bridges) are now constructed annually in the U.S., with 25% being true abutments supported directly on the reinforced soil (Anderson, et al., 2005). The main reasons for this growing usage are more rapid construction and lower cost of MSE abutments as compared to conventional concrete abutments.
MSE abutments – both true and mixed – should be designed using the Coherent Gravity method, discussed above and specified by AASHTO (2010), because the Coherent Gravity Method accounts for externally-applied loads and structure eccentricity.

BACK TO BACK WALLS

Back to back walls are commonly used as approach structures to vehicular and pedestrian bridges and for support of railways. Back to back walls consist of MSE structures with two wall faces separated by the width of the embankment. In some cases, the width of the embankment is narrow and the soil reinforcements from each face share the MSE backfill in the middle for pullout resistance. This is acceptable since the shear forces are in opposite directions.

Back to back walls with an aspect ratio (width of embankment divided by height) as small as 0.6 are safe and used in practice for many applications. The NHI, however, recommends that the minimum safe aspect ratio should be 1.1. This is not logical, as explained below:

The recommended aspect ratio for a standard MSE structure that retains a soil embankment is 0.7, but such an MSE structure may have an aspect ratio less than 0.7 if justified by calculation. Logically, therefore, if a structure with an aspect ratio of 0.7 can retain the soil load of an embankment, then a structure with the same aspect ratio certainly can stand alone, without an embankment to retain. The only load conceivably acting on a back to back structure is the wind load that may act on one face or the other. This load is far less than the load of a soil embankment. Clearly, the NHI-recommended minimum aspect ratio of 1.1 is incorrect.
CONCLUSIONS

The state of the practice of MSE wall design for highways has become more complex as more and more systems, engineers and researchers have become involved. There are correct ways to design MSE walls, to apply traffic surcharge, to select design parameters and backfill, to assess service life, to address special design conditions such as bridge abutments, traffic barriers and earthquakes, and to select the wall design method itself. Yet the complexity persists, arising from policy changes and from the multitude of conflicting design choices.

Designers are forced to be familiar with the Coherent Gravity, the Simplified (Tieback Wedge) and occasionally other methods, with the ASD and LRFD design platforms, with metric and U.S. customary units, with design guidelines issued by AASHTO and NHI, and with numerous, differing governmental specifications. Designers are understandably confused by the conflicting guidance and clarification is needed. This clarification can be achieved through the following steps:

- Continued and exclusive use of AASHTO specifications for MSE wall design
- NHI courses should teach material consistent with AASHTO
- Require the Coherent Gravity Method for design of MSE walls with inextensible reinforcements
- Require the Simplified Method for design of MSE walls with extensible reinforcements

Today's challenge is to restore basic principles to the design of MSE walls for highways to ensure that Mechanically Stabilized Earth structures continue to meet the structural and economic needs of transportation infrastructure for years to come.

REFERENCES


