REVIEW OF MECHANICALLY STABILIZED EARTH WALL PERFORMANCE ISSUES

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ABSTRACT: For approximately 35 years, Mechanically Stabilized Earth (MSE) walls have become increasingly popular in the development of transportation and other projects. The first U.S. MSE wall was constructed in California in the early 70’s. Since that time MSE walls have become generally accepted as a standard wall type on America’s Highways. MSE walls regularly reach heights in excess of 12-meters (40-feet) and can be technically and economically feasible to heights in excess of 30-meters (100-ft). Very few MSE walls fail completely, but there are many walls which haven’t performed as well as intended. In order to address this issue, several transportation departments have completed or are in the process of reviewing their design and construction practices in order to improve the overall performance of their MSE walls. Ten typical problems identified by these reviews are related to geometry and wall layout, obstructions, wall embedment, surface drainage, contractor experience, claims, backfill placement and compaction, panel joints, leveling pad, durability of facing. Furthermore, asset management techniques are recommended as a tool to help optimally manage and maintain MSE and other wall types.
WHAT ARE MSE WALLS AND WHY ARE THEY SO POPULAR?

Mechanically Stabilized Earth (MSE) walls are earth retaining structures that are constructed by placing alternating layers of reinforcement and compacted soil behind a facing element to form a composite material which acts integrally to restrain lateral forces. MSE walls are gravity structures that are relatively flexible and can tolerate horizontal and vertical deformations. Although MSE walls can be used in cut situations they are most efficient in fill or embankment applications. Figure 1 is an example of an MSE wall using pre-cast concrete facing elements.

![FIGURE 1 Pre-Cast Concrete Panel MSE Wall.](image)

Figure 2 illustrates the three primary MSE wall components. These three components work together to form the composite structure referred to as MSE. Because MSE is an integration of components, MSE walls are designed for external, internal, and compound stability. External stability analysis addresses sliding, bearing capacity, eccentricity, and overall stability modes of failure. Internal stability analysis addresses reinforcement rupture and interaction with reinforced fill and connection strength. Stability analyses also identify possible compound failure modes which initiate outside the reinforced zone and exit through the reinforcement and facing.

Reinforced fill is the soil that is used to construct the wall. Although it can be composed of a wide range of soil types, a well graded granular soil is the preferred material due to its strength, drainage, and durability properties. A well graded granular soil is also preferable for constructability and interaction with the reinforcement elements. Soils that are poorly graded or have a significant percent of fines (smaller than the No. 200 sieve) are much more moisture sensitive and are very difficult to place and compact.

Reinforcement elements are inclusions which are placed in layers within the fill material. Through their interaction with the surrounding soil and their tensile capacity they confine the soil and provide reinforcement. Reinforcing elements are made out of steel or geosynthetic materials. They are fabricated as strips, bar mats, geogrids, or fabrics and have a wide range of tensile strength and stiffness.
Facing elements provide erosion protection and confinement of the fill for placement and compaction. The facing is also the aesthetic component of the wall because it is all that will be seen. Typical wall facing elements are either precast or cast-in-place concrete panels, modular blocks, or wire facing. The various facing elements have different connection schemes to carry the required loads and attach to the reinforcement.

MSE walls have become increasingly popular primarily due to their low cost, ease of construction, and structural tolerance to foundation settlement. MSE walls have been found to have equal or better performance than more rigid wall systems under seismic loading events and MSE walls are technically and economically feasible to heights in excess of other wall types. Finally, the wide range of possible facing types, colors, and textures gives owners and architects the opportunity to design the wall to fit into the aesthetics of the site environment.

**GENERAL OBSERVATIONS**

Over the past several years there has been a disconcerting increase in the observation of poor performance of MSE walls. Most observations suggest poor performance is related to construction, although some can be attributed to design, wall and material selection, and mitigation of weak foundations. One of the advantages promoted for MSE walls is that they “Don’t require experienced craftsmen with special skills for construction” (Ellias, et al., 2001). This, we believe, is being taken to mean that these walls can be built by anyone. Projects may not have sufficient skilled labor on the contractor’s or owner’s team or budget on the owner’s team to provide adequate inspection with respect to construction details. This type of experience and budget is needed to review the submittals and inspect the construction.
FIGURE 3 Example of MSE wall poor Performance.

It has been difficult for owners to enforce performance specifications because MSE walls are generally on the critical path of the construction schedule and delays associated with rebuilding all or part of a wall can have indirect costs that far exceed the wall replacement cost. Once a wall is built it is very difficult to force the contractor to remove and rebuild it when it falls outside of specified construction tolerances. This is because the deficiencies appear aesthetic only and the costs and schedule implications to remove and replace are large. Unless there is a structural concern the wall will remain as is. Inspectors have not been able to make the contractors construct the walls according to the required performance specifications.

Several state transportation departments (DOTs) have been looking at specific performance issues by conducting internal reviews of their design and construction practices in an effort to improve their overall wall performance and durability. These reviews have been performed in formats ranging from a very informal process to a formal quality assurance review. Key observations from reviews conducted by Central Federal Lands Highway Division and the Arizona (DMJM Harris, 2007), Colorado (Liu, 2008), Ohio (Morris, 2006) (Ohio DOT, 2006) and South Carolina Departments of Transportation (DOTs) are reported here. There is a recurring theme to the observations and most are captured in the following list of design and construction inspection issues.

- **Design**
  - Geometry/wall layout
  - Obstructions
  - Wall embedment
  - Surface drainage
  - Contractor experience
- **Construction/Inspection**
  - Claims
Observations in each of these categories are summarized and recommendations are made to improve wall design, construction and ultimately performance.

**DESIGN ISSUES**

Design issues are associated with those items that owners can and should take into consideration when preparing plans for a contractor to bid on. These items deal with wall layout, managing surface water runoff, considering obstructions within the wall fill or those protruding through the face, and requirement for contractor experience.

1. Ohio DOT concluded that acute angles should be avoided and recommended preferred wall geometry at bridge abutments (Narsavage, 2006). Acute corners are difficult to construct due to the layering and skewing of the reinforcement, wall batter, and interference with obstructions such as piles or drainage structures. Placing and compacting fill in these corners particularly at reinforcement elevations can becomes more difficult.

If acute angles cannot be avoided due to other roadway design concerns, shop drawings from the wall supplier should address the construction concerns at these corners. These drawings should include as a minimum; special connection details, reinforcement orientation, and backfill placement and compaction procedures.

2. Wall obstructions such as piles in abutments, drop inlets, culverts, utilities, and traffic barriers are avoided by skewing or cutting reinforcements. These actions impact the internal stability of the wall and may impact long-term performance.

Plans for accounting for obstructions should be developed by the wall designer in advance of construction. Details for doing so can be unique to the different facing and reinforcement types. The project engineer should review and approve the details of how the obstructions will interact with the wall facing and reinforcement elements. Shop drawings should include all details required to address the specific project, which may mean that they are not off the shelf.

3. Retaining walls are designed to have a minimum embedment below finished grade to account for the stability of the wall (bearing capacity and overall stability) and for erosion or scour of the wall foundation. Observations from existing walls are that some walls are not adequately embedded. This may be the result of subsequent scour and erosion of the soil at the wall toe or it may be the result of inadequate embedment during construction. Scour and erosion are covered as part of Design Issue No. 4. Inadequate embedment from construction may be the result of differences in proprietary wall types. The photos in Figure 4 illustrate examples of inadequate embedment at the wall face that is believed to be the result of construction shortcomings and subsequent erosion.
The owner specifies the minimum requirements for wall embedment below finished grade based on the design for external and overall stability in addition to protection from scour and erosion. The wall supplier must then design the wall to accommodate the specific geometry of the selected facing elements. In many cases the wall may need to be set deeper due to the shape of selected facing elements. Consider, for example, that modular blocks can closely...
follow the terrain and 3-meter (10-foot) wide precast panels can not. These panels would need to be set deeper so that minimum embedment is met at all locations. Inspectors should check that the minimum wall embedment was used in the shop drawings and is being met at all locations during construction.

![Internal erosion of wall fill.](image)

**FIGURE 5** Internal erosion of wall fill.

4. Surface water runoff causes significant internal and external erosion of the fill and/or the foundation soils, as shown in Figures 4 and 5. Typical occurrences are concentration of water at wall ends, water flowing through the permeable facing fill, and concentrated flow overtopping walls. Figure 5 shows an example of the amount of internal erosion that has occurred when surface water is not managed properly.

Although managing surface water is an obvious issue that most designers understand needs to be considered, sometimes standard approaches have had unintended effects. For example, a curb can be overtopped and water, which is now channelized, can cause significant damage along a section of wall not designed to handle concentrated flow. Surface water runoff needs to be designed for during the roadway and wall layout stage. Collected water needs to be controlled until it is far enough from the wall that it can not impact the wall, or the wall needs to be designed so that it can sustain the concentrated flows.

Uniformly graded gravel can be and is used behind most wall facing systems for reasons including reduced compaction requirements and subsurface drainage. An unintended
consequence is that the facing rock has captured surface water runoff. Surface water has traveled through the gravel at the face and not only eroded the wall foundation in front of the wall, but directly beneath the wall facing. The gravel facing column then falls out the bottom of the wall. Figure 4(a) is an example of this condition on a wire face wall. Note the gravel directly below the wall facing.

Where overtopping by surface water is a possibility, especially in the coble size range, the need for using uniformly graded gravel at the face should be evaluated. If this material is desired, details should be developed to avoid damage from flow of water vertically through the facing rock. A low permeability cap could prevent infiltration and some type of permeable reinforcement can be installed at the base of the wall to retain the gravel while letting water pass.

5. One of the advantages often attributed to MSE walls is that “experienced craftsmen” are not required (Elias, et al., 2001). Perhaps as a result, some state DOT’s have none or insufficient experience qualification requirements for their MSE wall contractors. Despite having a qualifications clause, Colorado DOT concluded that their contracts were allowing contractors with insufficient experience on their projects. Their specifications did not adequately screen contractors.

The design issue here is with the preparation of construction documents. The specifications should have a clause that sets minimum requirements for experience as appropriate for the size and complexity of the walls in the contract. As a minimum, the specifications should include a minimum wall face area constructed of at least a certain height using facing and reinforcement elements required for the project.

CONSTRUCTION/INSPECTION ISSUES

1. There have been increased contractor claims on MSE walls for increased face area and earthwork volume. The shared design responsibility of this item lends itself to misunderstandings. Typically, the owner is responsible for the external (sliding, eccentricity, and bearing capacity) and overall stability of the wall. The owner is simply checking and verifying that this type of structure can work. Therefore, the owner sets the minimum reinforcement embedment lengths and wall embedment below grade to account for overall wall stability, erosion, and scour. The contractor is responsible for selecting the wall system which best suits their skills, needs, and access within the requirements of the specifications, and minimizes their cost. Therefore, the contractor and his supplier have to design the wall for internal stability, which includes reinforcement rupture and pullout.

There are two primary issues leading to claims. The first issue is an increase in wall face area due to increased wall embedment below grade. This is due to inefficiencies in the facing element which may not be able to step at the rate used by the owner. It can also be due to minimizing the number of steps the wall uses because it may be more efficient for the contractor to bury wall instead of constructing steps. In either of these cases, contractor choices of materials or methods should be based on satisfying project criteria, including minimizing cost and schedule, and should be included in the contractor bid. In most cases,
burying the wall deeper is not a problem from the owner’s point of view. When approving wall submittals, the owner should acknowledge the increased face area and reply to the contractor that they will not be paid for the additional quantities or they have the option to redesign.

The second issue is related to the actual internal stability design. Pullout of the reinforcement is dependent on several factors which include in general terms the overburden pressure, area beyond the failure plane, and the reinforcement interaction with the fill soils. In most situations with minimum reinforcement lengths equal to 70% of the wall height, good quality fill, and normal loading conditions pullout should not control. The supplier has several things they can do to make the reinforcement lengths work within the minimum length requirements. For example, they can increase the interaction by reducing transverse wire spacing or increasing wire diameter. They can also increase the pullout area by reducing the vertical and/or horizontal spacing. If they don’t do this but instead choose to use longer reinforcements they may end up with a design that requires more excavation and fill that the owner’s design. In these cases the owner should be clear about the acceptability of this change and who will bear the cost.

In summary, claims which increase material quantities and earthwork volumes due to the choice the contractor makes in selecting a wall supplier or designer should not be considered. There is a need to clarify in the specifications that payment will be based on plan quantities and that contractors need to account for their design choices in their bid prices.

![Figure 6](image_url)

**FIGURE 6** Example of wire face wall facing fill placement and wall bulging

2. Improper placement and compaction of fill placed along the face has caused bulging of facing elements in wire faced walls. Facing fill is a specially designed fill that compacts easily to a dense state and is free draining. Figure 6 (left) shows the typical fill placement process for wire faced walls. In this process, facing fill is placed near the face of the wire faced wall after the reinforced fill is already compacted with the next reinforcement layer in place. The fill is then placed and compacted along the face through the reinforcement layer. If the proper materials and process is not followed you can observe the bulging seen in
Figure 6 (center). When done properly with the proper materials, wire faced walls have performed very well as seen in Figure 6 (right).

This process of placing fill through reinforcement openings is also being used in some more rigid faced walls (pre-cast panels and modular block). Although the type of bulging seen in wire faced walls is not typically observed in the more rigid facing, settlement of the facing fill will cause shear forces at the connections. Contractors that use the procedure discussed above state that it helps them maintain panel alignment prior to placing the next reinforcement layer for the panel. The recommended practice when constructing a rigid face MSE wall is to place and compact the fill at the face of the wall up at the same rate as the rest of the wall fill. Most walls are built properly without facing alignment issues. Fill near the face should be placed in thinner 150-mm (6-inch) lifts and compacted with light hand operated equipment such as a plate tamper. See Figure 7 for an example of proper placement and compaction of fill near the wall face.

**FIGURE 7  Example of proper placement and compaction of fill.**

3. The most common facing for MSE walls on public roads is precast panels. The panels come in many different shapes, sizes, colors, and textures, but they all have one thing in common. They are all placed with a specific gap around the panel which is typically specified as 19-mm (3/4-inch). Common observations are that facing panels do not have the specified gap and protection against loss of material from between the panels is missing. Figure 8 (left) shows a set of panels which were not set properly and are touching. Figure 8 (right) shows a gap which is greater than specified.

In order for the wall to have the intended flexibility the precast concrete panels cannot touch. Once panels are touching, even small movement will cause chipping and cracking. For example a 19-mm (3/4-inch) gap is designed for a limiting differential settlement of 1/100 for panels less than 2.75-square meters (30-sf). The relationship between limiting differential settlement and joint spacing is discussed in Elias, et al., 2001. The vertical gap is set by bearing pads placed in between panels before the next panel is placed on top. The horizontal gap is set by the wall installer using clamps and wedges. The clamps and wedges are then
removed after the reinforcement and fill are placed and the panels can support themselves. The proper panel gap is an issue which should be addressed by the inspector early during construction to properly set expectations.  

![Figure 8 Joint spacing too tight (left), too open (right).]

A geotextile layer is used to prevent the erosion of the wall fill material through the gap at the wall face. The geotextile functions as a filter to retain the fill and allow water to escape through the wall joints. The inspector should make sure this material is as specified and is installed properly. The joint gap is also important for the geotextile because if the gap is too wide sunlight can enter and deteriorate the geotextile. Also the geotextile is not meant to span a very wide gap. The geotextile can be seen in Figures 6 & 7 covering the horizontal and vertical joins of the panel. Figure 8 (right) shows a gap that is about 3 times greater than it should be and fill material escaping between the wide panel joints. Figure 5 shows the internal erosion that occurred because the geotextile was left out or not designed properly.

![Figure 9 Incorrect leveling pad layout.]

4. Leveling pads for MSE wall facings are not a major component of the wall and are generally specified as unreinforced concrete. The key aspect of the leveling pad is that it is at the required location, grade, and level. The objective is to provide a smooth, uniform, and level surface to set the first row of panels or blocks. Leveling pads are not being constructed such that they meet this objective. Figure 9 (left) shows a panel face with excessive shims and a
very rough surface. Placing this many shims to support the panels may cause differential movement between the panel and the wall fill. Causing the panels to hang from their connections, this generates shear forces at the connection. The connection of the panel to the reinforcement is not design for this type of loading. Figure 9 (right) shows the panels overhanging outside the leveling pad.

It is recommended to use shims to account for slight imperfections of the leveling pad and/or facing element, but shims should be limited and only within the allowed tolerance (example: -3 to +6 mm of design elevation) of the leveling pad. This is a construction issue which should be addressed by the inspector prior to beginning construction of the first course.

5. Modular blocks and precast panels are sometimes deteriorating rapidly and are not meeting their design life. All facing types, including modular block, pre-cast panels, and wire facing have issues with respect to durability. The typical issues include corrosion of steel and deterioration of concrete. Due to walls typically being on the critical path in the construction schedules, inspectors may accept manufacturer certifications without doing much sampling and testing of the facing elements. In addition, inspectors with limited experience may or may not know all the testing protocols needed to understand the data they are receiving. Figure 10 shows the deterioration of concrete modular blocks (left) and pre-cast panels (right).

The material specifications need to be based on the environment the walls are being placed in. For example, salts in deicing chemicals not only cause corrosion of the reinforcement but under the correct climatic environment can deteriorate concrete, particularly dry-cast modular block. A good source for current research on the durability of segmental retaining wall blocks is (Chan, et al., 2007).

![FIGURE 10 Deterioration of MSE Wall Facing Elements.](image)

**MANAGEMENT OF MSE WALLS AS AN ASSET**

Retaining walls are an important part of the transportation system; they are an asset of each DOT. Because the walls are so diverse in their type, location, age and function they are difficult to manage as an asset without a specific tool and program. An asset management system is a tool that enables owners and operators to optimally allocate resources with certain management objectives in mind; for example, to minimize life-cycle cost. The observations on MSE wall
performance presented here show that there are performance issues and maintenance needs for MSE walls. Of course, all wall types are susceptible to aging and deterioration, so a system would ideally capture data for all wall types and allow comparison of performance and cost. A program to implement an asset management system will allow a DOT to do the following:

- Make more informed, cost-effective program decisions and optimize the use of existing highway funds and resources.
- Maximize transportation system performance.
- Minimize life-cycle costs and maximize return on investment.
- Measure and analyze performance of like assets.
- Improve asset preservation through the use of focused preventive maintenance efforts.

The timing of the DOT investigations into wall performance that are reported in this paper coincides with increases in the use of asset management systems for retaining walls. For example, Ohio, Colorado, FHWA - Central Federal Lands Highway Division, and Oregon now are creating inventories of MSE and other wall types. Inventories are an initial step towards management of the asset. In addition to quantifying the asset, they provide baseline data on condition and performance. In the future, repeat assessments of condition and performance will provide factual data on longevity and maintenance costs of MSE and other wall types. These data will allow the DOTs to make informed decisions on their wall asset, and take actions that would lead to optimal design, construction and use of MSE walls. Some leading examples of wall inventories are as follows:

- Oregon DOT is embarking on a retaining wall management program to inventory and assess their retaining wall asset across the state. The state estimates that they have approximately 10,000 retaining walls in their state, which are valued at $250 million (Oregon DOT web site).
- The City of Cincinnati has been using a retaining wall inventory and inspection system since 1990. The system allows the city to maintain a prioritized list of repairs and replacements based on regular inspections; in addition the system helps them respond rapidly to public concerns of their walls (City of Cincinnati web site).
- The National Park Service (NPS) and the FHWA Federal Lands Highway Office have recently implemented a retaining wall asset management program. Data have been collected for nearly 3,200 walls within 26 national parks around the country (Anderson, et al., 2008).

CONCLUSIONS

MSE walls have been designed and constructed in the United States for over 35-years. At this time, millions of square meters of wall face have been constructed. The authors estimate that currently MSE walls are being constructed at a rate of hundreds of thousand of square meters annually, and highway construction accounts for a significant percentage of this. MSE walls in general provide an economic solution to meet many project needs. However, observations from state DOT reviewers indicate that several design and construction issues commonly arise and lead to performance and longevity less than intended. We believe these issues are not inherent to
the MSE wall technology but are related to design and construction approaches and to the resources allocated to the design reviews and construction inspection.

The good news is that these issues can be avoided by allocating appropriate resources to review design submittals and inspection during construction. The staff providing these activities needs to have adequate training to perform these activities in an effective manner. The National Highway Institute has design, construction, and inspection certification courses. These courses should be taken by designers, inspectors, and wall installers. This is critical in order to give the designers and inspectors the confidence to defend the project specifications and performance requirements of the retaining walls. For the wall installers, these courses provide the background which helps them understand the reasoning for many of the design decisions and expectations of the owners.

Many of the design issues can be addressed by reviewing the specifications and design drawings addressing the issues discussed. The construction of MSE walls can be a relatively simple process, but it does require experience in order to construct it properly. Therefore, MSE wall installers should be required to have the experience in constructing retaining walls of the size and complexity being specified by the project.

Finally, owners should consider implementing an asset management system and program to manage their retaining walls. Early benefits are expected to be improved understanding of the size and condition of their walls as a whole. Longer term benefits will include optimizing selection of wall types based on project needs and performance data, implementing a data-based maintenance program, and the potential to optimize design and construction approaches based on recorded wall performance.

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