

TALL WALL MECHANICALLY STABILIZED EARTH APPLICATIONS

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ABSTRACT

This paper discusses the use of Mechanically Stabilized Earth (MSE) walls in ever increasing heights. Most MSE walls worldwide that exceed 20 meters high are constructed using metallic reinforcements in the reinforced volume. Design of tall MSE walls has much in common with design of lesser-height walls, but the performance of more detailed site investigations prior to design and the use of instrumentation monitoring during construction are critical to ensuring successful performance of these tall structures. Design features important to tall walls are described, and the paper cites several examples of completed tall MSE walls to demonstrate the international acceptance of such structures in major industrial and highway projects.

INTRODUCTION

Mechanically Stabilized Earth (MSE) technology is over 30 years old. As the technology has developed, it has evolved from discrete steel strips used as reinforcements to include metallic grid reinforcements and, more recently, geosynthetic reinforcements. The basic technology still remains unchanged, however, consisting of precast concrete facing panels, soil reinforcements and granular backfill. MSE walls derive their strength and stability from the frictional and mechanical interaction between the granular backfill and the reinforcements, resulting in a permanent and predictable load transfer from backfill to reinforcements that create a unique composite material. The selection of the reinforcement type plays a significant role in the design and performance of the MSE wall; this selection depends on wall

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geometry, physical site conditions and intended use. What is common among all MSE wall types is their greater flexibility and considerable economy compared to rigid gravity wall systems.

The greater acceptance of MSE technology has expanded the role of these structures from straight, low-height walls to taller structures with complex vertical and horizontal geometries. In the United States prior to the 1980s, MSE walls were generally used for heights of less than 12 meters. By the 1990s, construction of MSE walls approaching 20 meters gained acceptance. Though several reinforcement types are currently available for MSE walls less than 20 meters in height, the design and construction of walls taller than 20 meters has primarily employed discrete metallic strips or metallic grids.

Several dozen tall walls exceeding 20 meters high have been constructed worldwide using MSE inextensible (steel) reinforcements, with the highest being 41 meters. The need for tall walls in metropolitan areas is increasing due to space limitations, particularly along transportation corridors. Although some special considerations need to be made in connection with the appearance of these walls, the design and construction are based on the same concepts and materials used in walls of lower height. The inextensible steel reinforcements used in MSE walls prevent the significant deformations that would be expected in similar-height walls reinforced with extensible geosynthetic reinforcements, while permitting the flexibility under settlement that is a primary benefit of using MSE structures.

This paper discusses issues specific to tall MSE walls using steel reinforcements, including appearance considerations, subsurface investigations, design considerations for stability and deformation control, construction materials and quality control, and post-construction monitoring. Reference is made to walls already constructed to document the increased acceptance of and confidence in tall MSE walls.

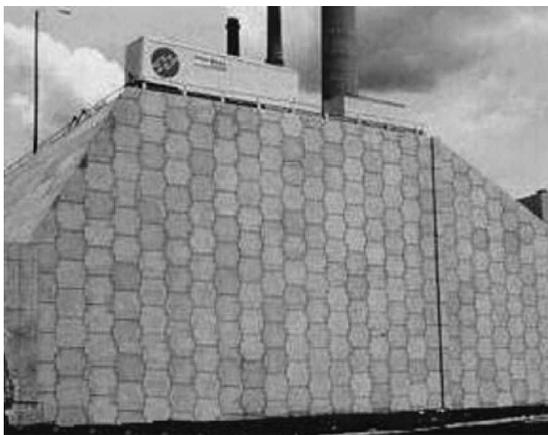
SUBSURFACE INVESTIGATIONS

Field investigations should always be performed prior to designing MSE walls to characterize foundation soils and soil strength parameters. For low to moderate height walls, test boring locations and other aspects of the subsurface investigation are typically confined to the front face alignment of the planned walls. This is usually satisfactory for such walls, but the significant width of the reinforced volume in tall walls means borings and other tests located only along the front face of the wall may miss important subsurface information. For the purpose of site investigation planning, then, the width of the MSE volume should be assumed to be 70% of the planned wall height [2] and soil borings should be staggered at maximum 30 to 45 meter intervals within the overall footprint of the preliminary wall volume. Borings may need to be spaced closer where weak or unsuitable subsoils are encountered for support of the intended MSE structure.

Tall wall geometries will result in significant foundation loads, necessitating a more comprehensive pre-design subsurface investigation than for lower walls (*e.g.*, a wall height of 20 meters with select fill density of 19 kN/m³ produces a bearing pressure approaching 380 kPa). Although MSE walls are flexible structures, this flexibility primarily influences wall deformation/settlement behavior, not wall bearing pressure. Soil strength and density can be assessed using Standard Penetration testing (ASTM D1586) and Cone Penetration testing (ASTM D3441) [3]. Undisturbed samples obtained from the test borings may be used for physical characteristics testing in the laboratory, and direct shear, triaxial and consolidation testing will yield an understanding of foundation strength conditions available for support of tall walls. In situ strength tests are also recommended, including dilatometer and/or pressuremeter testing, to aid in determining bearing capacity and estimating settlement of subsoils. The AASHTO “Manual on Subsurface Investigations” [1] provides further information on the type and extent of explorations that may be undertaken.

DESIGN

One of the first considerations in designing tall MSE walls is choosing between a single-face and a tiered wall configuration [Figure 1]. This decision has important stability, maintenance and aesthetic implications. Aesthetically speaking, it may be desirable to use tiers since tiered walls can better follow and blend into surrounding topography. Tiers also give tall walls a less imposing appearance, with even a short step-back effectively breaking up the potentially massive look of a tall wall. Maintenance is simplified by building a tiered structure, since the top of each tier provides access to the next-higher portion of the wall. While step-backs of as little as 1 meter can provide these aesthetic and maintenance benefits, a larger set-back is required to change wall stability factors.



*Figure 1a. Single Height Wall
Labadie Plant Slot, Missouri*



*Figure 1b. Tiered Wall
US 23 Unicoi County, Tennessee*

Stability Evaluation

The choice of an offset between tiers or a single vertical face directly affects the vertical stresses and the location of the line of maximum tension to be considered in design. Simplified guidelines for determining the maximum tension lines are shown in Figure 2 [4]. The delineation of the maximum tension line is used to locate where pullout resistance is mobilized through one or a combination of the two basic soil-reinforcement interaction mechanisms, i.e., interface friction (discrete strips and grids) and passive soil resistance against transverse elements of composite reinforcements (grids). Notice that a small offset between tiers does not result in a significant difference in the maximum tension evaluation compared to a wall with a vertical face.

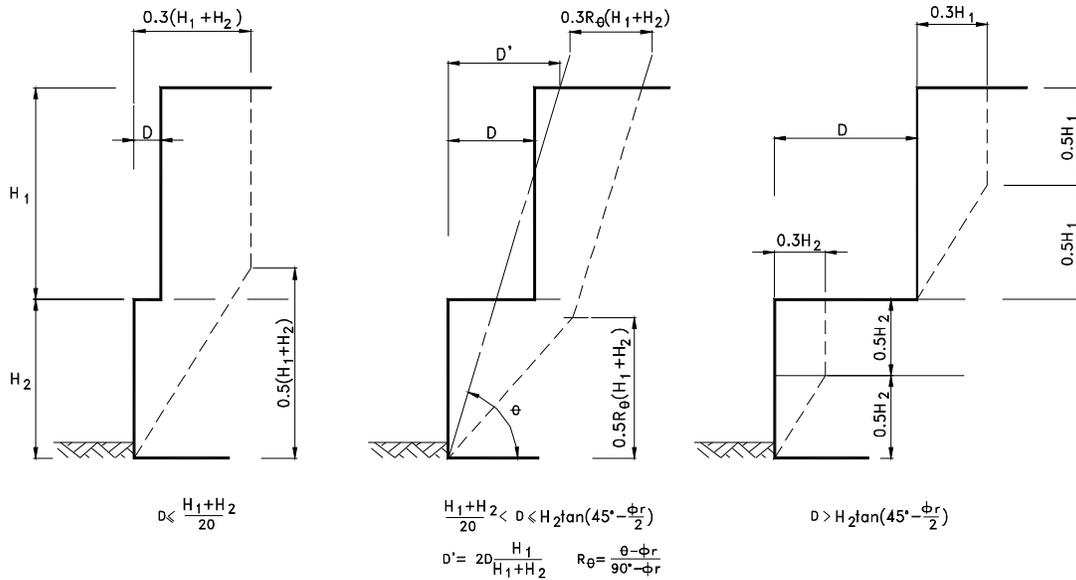


Figure 2. Maximum Tension Lines

Internal stability may be calculated on the basis of the lines of maximum tension. For tall MSE walls, tensile resistance controls the internal design since bond resistance is of less consequence than for lower height walls. Though either steel strips or steel grids may be considered in tall MSE wall applications, it is reinforcing strips that have typically been installed in walls with design life exceeding 75 years. Steel reinforcing strips are typically 4 mm thick but, as walls approach and exceed design heights of 30 meters, it often is necessary to increase strip thickness to 5 or 6 mm to keep the number of strips per panel to no more than 20. This practical limit is dictated by the size of the nominal 1.5-meter square concrete facing panels and the required spacing between the galvanized tie strips that are embedded in the panels to anchor the reinforcing strips. Increasing panel size is not a viable option, for reasons discussed under *Deformation* below. Where necessary, panel thickness may be increased from 140 mm to 190 mm to accommodate the higher stresses toward the bottom of taller walls.

In standard height MSE walls, the evaluation of sliding resistance is performed as a check on external stability, but slope stability analysis gives a better check on external stability for taller MSE walls. Failure slip circles, evaluated as part of the slope stability analysis, should be located to pass through individual tiers and through the toe of the wall at its base. The failure circles should not be confined to the internal reinforced volume of the MSE wall, but should also be located both internal to and immediately external to the reinforced volume, effectively resulting in a composite stability evaluation. Overall global stability should be checked as a final evaluation of the entire tall wall and its supporting foundation, whether soil or bedrock.

Bearing Capacity

The competence of the foundation bearing soils must be well understood when designing taller walls due to the larger loads imposed and the economic impact of unnecessary conservatism. As noted in the discussion of the subsurface investigation, above, a thorough evaluation of the in situ strength will allow greater confidence in assigning reasonable and appropriate bearing capacities, resulting in a more economical design. Under allowable stress design, a factor of safety of 2.0 is considered reasonable for MSE walls when a comprehensive subsurface investigation has been performed in accordance with AASHTO guidelines [2], so there is a clear incentive to conduct a thorough examination. Conversely, a less comprehensive subsurface examination can force the use of higher safety factors, resulting in a more expensive design.

Deformation

It bears repeating that a thorough site investigation, including in situ strength evaluation and appropriate consolidation design, increases the likelihood that a tall MSE wall will be economically designed. Design economy is further enhanced by the use of finite element modeling (FEM) which allows a more thorough analysis of MSE walls under both static and seismic conditions. Results of stability calculations may be used to determine possible failure slip circles, which may in turn be used to evaluate the stresses within the reinforced volume and predict wall deformations.

A horizontal deformation of approximately 12 mm is typically considered necessary in order for the inextensible steel strips to develop full load transfer with the granular backfill (pullout resistance). Further horizontal deformation will not significantly affect the structural integrity of the MSE walls. In one extreme example, horizontal deformation in excess of 100 mm has been measured in Reinforced Earth[®] walls after seismic events [5], but with no loss of structural integrity. Minimizing deformation is still desirable, however, to control appearance and to compensate in advance for possible construction deficiencies. Based on FEM analyses, critical deformations appear to occur in the middle third of the tall wall height, so additional reinforcing strips and/or additional reinforcement length may be considered to reduce such horizontal deformations predicted during design.

Tall MSE walls readily accommodate vertical deformations resulting from settlement within the internal reinforced volume and/or within the foundation bearing soils. As with all MSE walls, tall walls are flexible compared to non-MSE retaining walls. This flexibility derives from the use of wire facing panels or relatively small, nearly square-shaped precast concrete facing panels (1.5 m x 1.5 m) that are designed to allow small panel-to-panel movements to occur, thereby distributing larger total movements over a wide area of the wall. Elastomeric bearing pads, located in the horizontal joints between facing panels, maintain separation but allow for controlled compression. These pads range in thickness from 19 to 25 mm, with the thicker pads used lower in the wall to provide greater separation and compression resistance due to the higher loading. Computations performed for the 25 mm thick pads indicate they are effective for wall heights up to 50 meters.

Large total deformations may be tolerated by MSE walls, with total settlement in excess of 1 meter observed in some tall structures. Differential settlement must be carefully considered, but the flexible nature of the reinforced volume, combined with the bearing pads in the panel joints, allows MSE walls to tolerate up to 1% differential settlement (an angle of distortion up to 1 cm/meter), compared to the typical 0.1% differential settlement tolerance of cast-in-place concrete walls. A thorough site investigation followed by deformation analysis may allow the designer to take full advantage of this inherent MSE wall flexibility.

CONSTRUCTION CONSIDERATIONS

The successful performance of MSE walls depends as much upon the select backfill as on the steel reinforcements used in the reinforced volume. Standard design practice per AASHTO criteria [2] considers select fills that are electrochemically stable, have low fines content (less than 15% passing the No. 200 sieve), and have a friction angle of at least 34°. The granular fill promotes consistent frictional performance and drainage, while maintaining the integrity of the steel reinforcements against severe metal losses. Though walls of lesser height may occasionally use select fills that vary from these criteria, it is important to maintain the more stringent material requirements in tall walls.

Installation

The availability of large quantities of granular select fill is, in itself, an important way to assess whether construction of a tall MSE wall should be undertaken. The volume of select fill is far from inconsequential, since the reinforced volume has a minimum width of 70% of the height. The select fill is placed in controlled and compacted lifts while placing reinforcements and maintaining the overall plumbness of the panels at the front face. The granular soil allows a greater degree of alignment control as the panel is positioned, since compaction may be readily achieved with less effort and, therefore, less risk of panel movement. Panel alignment at the base of tall walls is especially critical, since it directly influences development of a plumb and aligned wall face at successive upper levels.

The use of granular select fill ensures that the wall system has positive drainage attributes, but control of runoff, both during construction and permanently, is critically important. Depending on the surrounding topography, this runoff control may be needed well away from the immediate area of the wall. Tall MSE walls that have tiers can make use of lined drainage trenches at each level to capture and dispose of runoff in a controlled manner, in addition to drainage measures implemented on top of and below (in front of) such walls.

Instrumentation and Monitoring

Tall MSE walls should be considered critical structures, meaning instrumentation and monitoring of these walls is a necessary part of the design and construction process. The selection of instrumentation is based upon features encountered during the site investigation (subsoil characteristics, groundwater and area seismicity, to name a few), as well as the size of the wall. Instrumentation locations are generally selected at maximum wall heights, near changes in tiers, and at intermediate/regular spacing. While there is no pre-set instrumentation list for all projects, the following six types of instruments should be considered: survey points on panel faces, inclinometers, stress cells, strain gauges, strong motion detectors and pneumatic piezometers.

Survey points are the most widely used method of monitoring, simply by measuring settlement on progressive days using measurements of set points on the wall face. Inclinometers may be used to evaluate internal, external and global stability of the RE volume. Stress cells are used to monitor the internal volume for tensile stresses, while strain gauges mounted at regular intervals directly on the strips measure reinforcement deformation. Use of strong motion detectors and piezometers will depend upon the potential, if any, for seismic or high pore pressure conditions, respectively. A well-planned instrumentation program will have overlapping monitoring available in the event that one set of instrumentation is disturbed or destroyed during construction.

Instrumentation to monitor tall MSE walls should be supplemented by installation and retrieval of reinforcing strip durability samples. Monitoring the durability of the galvanized steel strips is even more important than surveying the movements of the wall or reading the tensile loads in the strips. Evaluations of metal losses at specific periods in the life of the wall may be conducted in accordance with the FHWA Corrosion Manual [6] to confirm expected behavior. This undertaking will require long term planning, with samples pulled for analysis at regular 10 to 15 year intervals over the typical 75- or 100-year design life. Locations for the durability samples will be primarily at the top of single face walls or of individual tiers, where an environment of relatively more oxygen and runoff is available to accelerate metal losses. Durability samples may be pulled out with a hydraulic jack using procedures similar to those adopted by the California Department of Transportation.

TALL WALL SUMMARY

A selected summary of tall MSE walls constructed worldwide is provided in Table 1. Note that in the United States, acceptance of tall walls has progressed from industrial/mining applications to major highway structures and, most recently, airport runways.

Table 1

<i>Location</i>	<i>Max. Height(m)</i>	<i>No. of Tiers</i>	<i>Year Complete</i>	<i>Comments (Supplier)</i>
De Beers "Tweepad", South Africa	41	1	1979	Diamond mine crusher headwall still under continuous operation. (RECo)
Labadie Plant Slot, Missouri (USA)	20	1	1981	Supports open coal slot. (RECo)
Tsing Yi Island, Hong Kong	40	6	1993	Maximum total settlement of 350mm & lateral displacement of 125 mm. (RECo)
Santa Barbara Primary Crushing Retaining Wall Antofagasta, Chile	22	1	1994	2:1 Infinite fill; 0.3g seismic acceleration. (Hilfiker)
Unicoi County, Tennessee USA	28	3	1994	Offsets of 11 meters between tiers, high friction backfill. (RECo)
Pont de Normandy, France	24	1	1995	Extensive tests performed on wall components to adapt to terrain. (RECo)
Kennedy Interchange, Atlanta, Georgia USA	30	3	1996	Setback of tiers at 2 meters. (RECo)
Antelope Mine Expansion Campbell County, Wyoming USA	22	1	1997	Scoria rock backfill. (Hilfiker)
Crusher Retaining Wall Smokey Valley Mine, Nevada USA	23	1	1997	Designed for 0.25g seismic acceleration. (Hilfiker)
Kemess Mines South Project, British Columbia, Canada	32	1	1997	Designed to support 830,000 pound haul trucks. (Hilfiker)
Bingham County Truck Dump Reloads Copperton, Utah USA	38	1	1999	Wall instrumented by Utah State University. (Hilfiker)
Mine Highway, Arizona USA	24	1	2000	Hybrid RE wall with precast concrete and wire fascia. (RECo)

Continued

<i>Location</i>	<i>Max. Height(m)</i>	<i>No. of Tiers</i>	<i>Year Complete</i>	<i>Comments (Supplier)</i>
Crushing System Expansion, Victor, Colorado USA	32	1	2001	Mine wall supporting bridge crane. (Hilfiker)
Route 288, Richmond, Virginia USA	24	2	2002	High friction (gravel) backfill. (RECo)
Springfield Interchange, Virginia USA	20	1	2002	High friction (gravel) backfill. (RECo)
Hartsfield Airport Runway, Georgia USA	20	1	2003	Maximum total settlement of 600 mm during construction. (RECo)



Figure 3a. Route 288, Richmond, Virginia *Figure 3b. Hartsfield Airport, Georgia*

CONCLUSIONS

Tall MSE walls provide an increased opportunity to take advantage of the superior economy and ease of construction afforded by MSE technology. Since tall walls result in more significant loading of the bearing soils or bedrock, a comprehensive site investigation is of critical importance. The design process is similar to that for lower height walls, though composite stability evaluations and deformation analyses play a more substantial role in developing the internal and external designs. Steel-reinforced MSE walls have proven to be an economical, reliable system for tall wall applications, with materials that meet the demands of greater loading while maintaining flexibility and ease of construction.

REFERENCES

- [1] Manual on Subsurface Investigations, AASHTO (1988).
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[3] Annual Book of Standards, ASTM (2002), Volume 4.08.

[4] Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines, FHWA Demonstration Project 82 (1997), Figure 47.

[5] Sankey, J.E. and Segrestin, P. (2001). "Evaluation of seismic performance in MSE structures." *Landmarks in Earth Reinforcement, Volume 1*. Proceedings of the International Symposium on Earth Reinforcement, Kyushu, Japan. pp 449-452.

[6] Corrosion/Degradation of Soil Reinforcements for Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, FHWA Demonstration Project 82 (1997). pp 26-46.