CHAPTER 3 — SMSE WALL DESIGN BASIS

This chapter provides a discussion of the basis for SMSE wall design, based on model testing (centrifuge and field-scale), numerical modeling, and a review of available literature. Recommended general design requirements for SMSE walls follow later in this chapter.

3.1 SMSE WALL RESEARCH REVIEW

Research conducted to assist in development of these design guidelines included review of available literature, scaled centrifuge model testing, instrumented load testing of a field-scale (prototype) test wall, and numerical modeling of the field-scale test wall. The literature review is presented in appendix A, and the procedures and results of the centrifuge modeling, field-scale testing, and numerical modeling are presented in detail in appendices B, C, and D, respectively. The following sections summarize the conclusions judged significant from a design standpoint for each of the various research efforts.

3.1.1 Literature Review Summary

The literature review, summarized in appendix A, provided the following results pertinent to SMSE wall design:

- MSE walls have been successfully constructed with reinforcement lengths shorter than 70 percent of the wall height ($<0.7H$), and use of MSE reinforcements on the order of $0.6H$ are common in the private sector.
- MSE reinforcement lengths considerably less than $0.7H$ have been successfully employed where the earth pressures are less than active earth pressures ($K<K_a$), as with MSE walls constructed in front of rock outcrops.[5]
- For narrow or confined walls, the vertical overburden stress may be less than the unit weight of the overburden multiplied by the wall height ($\sigma_v<\gamma H$) due to arching effects; where these effects occur consider the use of narrow or stepped walls.[6]

3.1.2 Centrifuge Modeling Summary

A discussion of centrifuge modeling procedures and results is presented in appendix B. The centrifuge method was effective for economically evaluating many different geometric configurations of SMSE walls. The following conclusions from that work are pertinent to the design of SMSE walls:

- Aspect ratios greater than 0.6 exhibited internal failures (all reinforcement layers intersected the failure plane) under increasing gravitational levels.
- Aspect ratios in the range of 0.25 to 0.6 generally produced stable wall systems that required a high gravity level for failure. These walls generally exhibited outward deformation

followed by compound wedge failure as gravity increased. The "toe" of the failure wedge was typically about one-third the wall height above the base of the MSE mass.

- Aspect ratios of 0.25 and smaller generally produced outward deformation followed by an overturning collapse of the MSE mass under increasing gravitational levels.
- At aspect ratios less than 0.6, deformation produced a "trench" at the shoring interface, interpreted to be the result of tension. The "trench" was not observed with aspect ratios of 0.6 or greater.
- A conventional MSE wall with retained fill and an aspect ratio of 0.3 was observed to be stable up to an acceleration level of 80*g*, which represents a prototype height of approximately 27 meters.
- The wedge failure geometries of SMSE walls were observed to be flatter than the traditional Rankine failure wedge assumption (i.e., $45^o + \phi/2$).
- Wrapped-back MSE reinforcements (where the MSE reinforcements in contact with the shoring wall are wrapped around the reinforced soil mass) resisted the tendency for toppling or overturning failure exhibited with other short MSE reinforcement configurations.(5)
- Smaller reinforcement vertical spacings provided increased stability.
- Moderate batter of the shoring interface appeared to improve stability.
- Qualitative agreement was apparent between the centrifuge test results and the numerical modeling results presented in appendix D.

Based on the centrifuge test results, details of the field-scale test were developed. Centrifuge testing was then conducted on a model of the field-scale test to predict its behavior.

3.1.3 Field-Scale Test Summary

Procedures and findings of the field-scale test are presented in appendix C. The following conclusions from this work are pertinent to design of SMSE wall systems:

- The constructed test wall was extremely stable, even under unrealistically high footing surcharge loads.
- Measured vertical stresses in the MSE mass appeared to reasonably approximate hydrostatic pressures (γH). However, some evidence of arching was apparent in the lower portions of the MSE mass near the shoring wall interface. This was most apparent in comparison of the two pressure cells at the base of the MSE mass, where measured vertical stress was consistently lower near the shoring wall.

- The "2:1 method" of estimating vertical stresses imposed by a surcharge was reliable for low stresses. At high stresses, this method was not reliable, so measurements of vertical and horizontal stress (σ_v and σ_h) were different than expected.

- The apparent earth pressure coefficient (K_r) at the interface between the shoring wall and the MSE wall was not a constant, becoming smaller as surcharge was applied.

- Reinforcement strains were similar between connected and unconnected wall systems.

3.1.4 Numerical Modeling Summary

Results of numerical modeling conducted to further evaluate the behavior of the field-scale test wall are presented in appendix D. The following conclusions from this work are pertinent to design of SMSE wall systems:

- The numerical model provided reasonable qualitative agreement with the field-scale and centrifuge testing.

- The numerical model predicted that SMSE walls constructed according to these design guidelines are stable.

- Quantitative prediction of wall behavior using the numerical model was very sensitive to compaction effects and related soil properties.

- The model predicted mobilization of shear stress along the shoring wall interface. This phenomenon was not directly observed in the field or laboratory testing; however, it may be inferred from the difference in vertical stresses measured at the base of the MSE mass.

- Predicted strains in the MSE reinforcements for the numerical model were qualitatively similar to the strains measured during field-scale testing.

- The numerical model predicted possible tension along the shoring interface.

3.2 APPLICATION OF RESEARCH RESULTS TO DESIGN OF SMSE WALLS

Based on centrifuge modeling, field-scale testing, and numerical modeling, a minimum MSE reinforcement length equivalent to 30 percent of the wall height (aspect ratio of 0.3) has been selected for design of SMSE walls. Centrifuge modeling of SMSE wall systems indicated that aspect ratios on the order of 0.25 to 0.6 produced stable wall configurations. The field-scale test was stable at an aspect ratio ranging from 0.25 at the base to approximately 0.39 at the top under excessive surcharge loading. Additionally, centrifuge modeling indicated that a conventional MSE wall with a retained backfill and an aspect ratio of 0.3 was stable under high levels of gravitational acceleration. The literature review further supports design of SMSE walls with a minimum aspect ratio of 0.3 when supported by permanent shoring wall construction. Centrifuge testing indicated that SMSE walls with aspect ratios less than 0.6 exhibited deformation in the form of "trench" at the shoring interface, believed to be indicative of tension cracking. Trench development was not observed for shored MSE walls with reinforcement lengths of 0.6*H* or greater. These design guidelines recommend that the upper two layers of MSE reinforcement have a minimum length of 0.6*H* to limit the potential for tension cracking at the shoring interface.

Centrifuge modeling showed that certain aspect ratios (i.e., less than 0.3) can theoretically induce sliding and overturning failures of the MSE component. However, the earth pressures affecting the MSE component are a result of self-induced earth pressures, and these pressures are unrealistic for sliding or overturning failure for routine wall batters and MSE aspect ratios of 0.3 or greater. This is because relatively small lateral strain is sufficient to relieve these earth pressures. As such, the design guidelines presented in chapter 5 do not include separate analysis of the MSE component for sliding or overturning failure modes. The minimum upper reinforcement length of 0.6*H*, also recommended based on the centrifuge test results, should counteract effects of these potential failure mechanisms.

An analytical approach is recommended for design of SMSE walls. Toppling failures of SMSE walls with short MSE reinforcements were observed in the centrifuge modeling as a result of self-induced earth pressures, as discussed previously. Measurements of lateral earth pressures recorded during the field-scale test imply that these pressures are less than active earth pressures. The degree of difference between active earth pressures and the actual self-induced lateral pressures appears to be strain dependent. The design procedure provided in chapter 5 is inherently conservative because it recommends use of the active earth pressure coefficient (K_a) and the lateral earth pressure coefficient (K_r). This is done to be consistent with current design methodology for MSE walls. As design methodology evolves, it would be appropriate to re-evaluate this recommendation.

Centrifuge testing, numerical modeling, and field-scale testing suggest construction of the shoring wall at a nominal batter to improve stability of SMSE walls. Centrifuge modeling evaluated the effects of vertical and battered shoring walls with nominal batters of 1H:14V (horizontal:vertical) and 1H:6V; stability of battered walls was observed to increase over vertical walls. Field-scale testing of an SMSE wall with a shoring wall batter of 1H:6V proved to be stable under significantly high loading. As a result, a shoring wall batter of 1H:14V or flatter is recommended to increase stability of the overall system.

Smaller reinforcement vertical spacings were demonstrated to provide increased stability to the SMSE wall system. Based on the results of centrifuge modeling, a maximum vertical reinforcement spacing of 0.6 m is recommended for construction of SMSE walls. This is also consistent with FLH standard practice for MSE walls.

Numerical modeling and field-scale testing indicates the potential for arching near the base of the MSE wall at the shoring interface for walls employing aspect ratios on the order of 0.25. Current practice for design of MSE walls with non-rectangular or stepped wall geometry recommends a minimum aspect ratio of 0.4 for the lower reinforcements when the wall is founded on rock or competent soil.[1,2] A forensic study conducted by Lee et al. on several failed stepped MSE walls with rock forming the foundation and the backslope for the lowermost portion of the wall suggests that the calculated vertical stress distribution at the back of the lower reinforcements is greater than the actual stresses because the stiffer rock behind the reinforcements encourage the formation of arching above the reinforcements.[51] As a result, design calculations likely overestimate the resistance to pullout, translation, and wedge failure for stepped structures adjacent to rock or other self-supporting backslopes (i.e., shoring). Based on these observations, the factor of safety against reinforcement pullout should be increased from 1.5 to 2.0 for wall aspect ratios less than or equal to 0.4.

3.3 SMSE WALL DESIGN CONSIDERATIONS

The following sections provide general details and recommendations for design of SMSE walls. Many of the recommendations were developed as a result of the literature review, centrifuge modeling, field-scale testing, and numerical modeling discussed previously. Others are based on current MSE wall practice as referenced below.

3.3.1 Backfill Selection

The design recommendations provided in this report are valid only where select granular fill material is used for the reinforced fill zone of the MSE component. Use of select granular fill for MSE wall construction is generally consistent with current transportation practice. However, careful selection of fill is particularly critical because of the shorter reinforcement lengths and a potential for reduced vertical stress due to soil arching near the shoring wall. Select granular fill for an SMSE wall should meet the following minimum specifications:

- The fill should be free from organic or other deleterious materials because the presence of these items enhances corrosion of steel reinforcements and results in excessive MSE wall settlements.

- The fill should be free draining and have a minimum friction angle of 34 degrees, as determined by laboratory direct shear (AASHTO T-236) or triaxial shear (ASTM D4767) testing.[7, 8] An example specification for select granular fill for SMSE walls is presented in table 1. However, the frictional strength of the specific material gradation provided requires verification for the available material source. Gradation analyses should be conducted using the AASHTO T-27 and T-11 methods, and the backfill should have a plasticity index (*PI*) as determined by AASHTO T-90 less than or equal to five.[7]

- The backfill materials should be free of shale or other soft, poor durability particles, and have a sodium sulfate soundness loss of less than 15 percent after five cycles. Testing should be in accordance with AASHTO T-104.[7]

Table 1. Select granular fill gradation example specification.

U.S. Sieve Size	Percent Passing[1]
100 mm[1,2]	100
75 mm	75 – 100
No. 4	20 - 70
No. 200 (0.075 mm)	0 – 10

1 In order to apply default pullout resistance factor (F^*) values (see chapter 5), the uniformity coefficient (C_u) should be greater than or equal to 4.

2 The maximum particle size for use with geosynthetics and epoxy-coated reinforcements should be reduced to 19 mm unless full-scale installation damage tests have been conducted in accordance with ASTM D5818 to evaluate the extent of construction damage anticipated for the specific fill material and reinforcement combination.(9) This also applies to epoxy-coated steel reinforcements.

The specifications provided in *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* (FP-03) address construction of MSE walls in section 255.(10) However, modification to these specifications is typically accomplished for FLH projects through Special Contract Requirements (SCRs) and likely is also justified for construction of SMSE walls due to their unique nature. Section 209.11 of FP-03 does not provide an allowable range of moisture content for compaction of reinforced backfill, but instead states that the moisture content should be adjusted such that the material is suitable for compaction; this is considered acceptable due to the granular nature of the backfill material. The maximum compacted lift thickness specified in section 209.10 of 150 millimeters is recommended to be maintained for SMSE wall construction. According to section 209.11 reinforced backfill should be placed and compacted to at least 95 percent of the maximum density as determined by AASHTO T-99 method C.(7, 10) However, where the stabilized volume supports spread footings for bridges or other structural loads, the upper 1.5 m should be compacted to at least 100 percent of the maximum density, per section 255.05.(10)

The compaction requirements for backfill close to the wall facing (within 1 m) differ because lighter compaction equipment may be used to limit lateral pressures and facing movement. A backfill material having good frictional and drainage characteristics, such as a crushed stone, is generally recommended close to the face of the wall to provide adequate strength, ease of compaction, and tolerable settlements.(2) Often, wire-faced MSE walls are constructed with nominal 0.1 to 0.2 m rock material manually-rodded into place at the wall face; such practices are appropriate to SMSE walls. Granular fill containing just a few percent fines may not be free draining. As such, drainage requirements of the SMSE wall should be carefully evaluated.

Backfill specifications for traditional MSE walls may differ from the backfill specifications for SMSE walls due to differing performance requirements or construction methods and constraints. Suppliers of MSE wall systems have their own criteria for reinforced backfills, but these criteria should be carefully evaluated for use with an SMSE wall system. Project backfill specifications which apply to all MSE wall systems should be provided by FLH or any other contracting agency.

Peak shear strength parameters are used in design of the MSE wall component. A lower bound frictional strength of 34 degrees is generally consistent with the select backfill specification provided in table 1, but should be verified through strength testing. Higher shear strength values may be used for design if substantiated by laboratory direct shear (AASHTO T-236) or triaxial shear (ASTM D4767) testing.[7, 8] However, caution is advised for design use of friction angles above 40 degrees due to lack of field performance data.[2]

Electrochemical tests (i.e., pH, resistivity, chloride content and sulfate content) should be conducted on the backfill to enable evaluation of reinforcement and facing connection degradation. Refer to FP-03 specifications or AASHTO Division I section 5.8.6.1 and Division II section 7.3.6.3 for guidance regarding recommended electrochemical properties of select granular backfill for use with steel and geosynthetic reinforcements.[1, 10]

3.3.2 Geometric Considerations

This section discusses geometric considerations for the MSE wall component of an SMSE wall system, including recommended minimum reinforcement lengths, shoring interface geometry, interface connections, and foundation or toe embedment.

MSE Reinforcement Lengths

Current public transportation engineering practice in the U.S. prescribes a minimum reinforcement length of 70 percent of the wall height (i.e., 0.7*H*) for MSE wall construction, with longer reinforcement lengths possible for structures subject to surcharge loading, sloping toe conditions, or a slope above the top of the wall.[1,2] For the private sector, NCMA prescribes a minimum reinforcement length of 0.6*H*.[11] Where an SMSE wall system is provided, MSE reinforcement lengths shorter than the generally accepted minimum of 0.6*H* to 0.7*H* are considered appropriate due to the reduction in lateral earth pressures acting behind the wall, as well as the contribution to global stability provided by the shoring system. A reduction in reinforcement length for the MSE wall component is appropriate whether or not the MSE reinforcements are connected to the shoring wall. In general, lengths for the MSE wall component should be designed primarily to provide internal stability of the MSE mass, whereas global stability should be evaluated for the entire SMSE wall system.

Centrifuge modeling (appendix B) and field-scale testing (appendix C) indicate reinforcement lengths as little as 0.25*H* provide sufficient wall stability, even under a considerably high degree of surcharge loading. Using these results, a minimum reinforcement length of 0.3*H,* as measured from the top of the leveling pad, is recommended for design of the MSE wall component of an SMSE wall system. It is also recommended that the reinforcement length not be less than 1.5 m, which is less than the 2.4 m minimum reinforcement length set forth in AASHTO and Elias et al. for traditional MSE walls.[1,2]

Specification of a uniform reinforcement length is not recommended for SMSE walls with battered shoring walls. Instead, it is critical that the MSE reinforcements extend to the shoring wall interface. A tolerance of 50 mm is recommended for this interface. Note that reinforcements may be bent upwards along the shoring wall interface, within the 50 mm tolerance.

Where adequate construction space is available (or can be made temporarily available), it is recommended that the upper two layers of reinforcement are extended to a minimum length of 0.6*H* or a minimum of 1.5 m beyond the shoring wall interface, whichever is greater, as illustrated in figure 6. This feature limits the potential for tension cracks to develop at the shoring/MSE interface, and resists lateral loading effects. If extension of the upper reinforcements is not feasible, a positive connection between the upper two or more reinforcements and the shoring wall is recommended, as discussed in the next section.

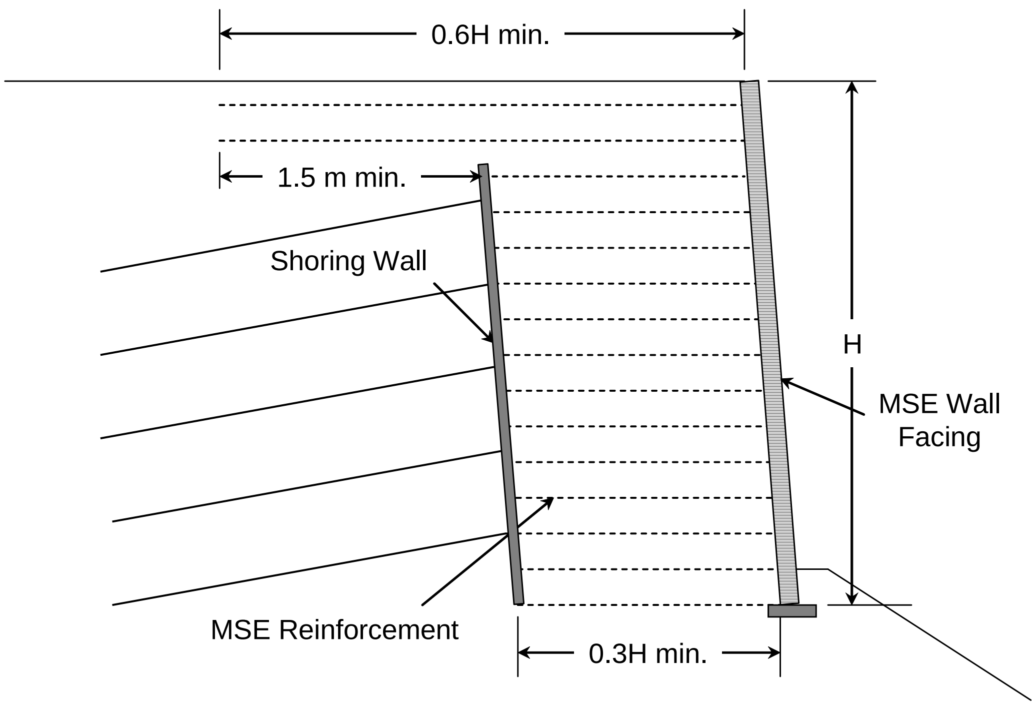


Figure 6. Diagram. Proposed geometry of MSE wall component of an SMSE wall system.

Extension of the upper two layers is intended to result in a wall cross section as depicted on figure 6, where the height of the shoring wall is at least 2/3 the MSE wall height (*H*). These guidelines should only be applied to wall designs that meet this constraint over the majority of their length. Walls with short shoring walls (less than 2/3*H*) over most of their length are outside the scope of these guidelines.

It should be noted that near the ends of the retaining wall the height usually tapers, and the shoring wall height may be less than 2/3 of the MSE height for a short distance. However, application of these guidelines will result in MSE reinforcements not less than 3 m long at the top of the MSE wall (1.5 m minimum *plus* 1.5 m minimum). Where the shoring wall is less than 2/3 of the height of the MSE wall, as may occur as the wall ends taper, the engineer should check to assure that reinforcement lengths in the upper part of the MSE mass is greater than the conventional 0.7*H* directed by AASHTO and Elias, et al.[1,2] Generally, this will be satisfied, as long as the total retaining wall height in such sections is less than about 4 m.

Interface Connections

Connection of the upper two or more MSE reinforcements to the shoring wall is recommended when extension of the upper MSE reinforcements beyond the limits of the shoring wall is not feasible. This concept is illustrated in figure 7. Though field-scale testing of an SMSE wall system demonstrated little benefit of a connected versus an unconnected wall system (see appendix C), this recommendation is made based on MSE wall experience with cracks forming at the back of the reinforced fill mass and observation of the "trench" during the centrifuge tests. Incorporation of interface connections may limit differential movement between the shoring wall and MSE wall components, as a result limiting development of a tension crack, especially if the slack in the MSE reinforcements can be effectively removed. This could potentially be accomplished through the fastening mechanism or by surcharge loading. Extension of the upper MSE reinforcements is considered superior to mechanical connection of the reinforcements. Similar performance (lack of separation or cracking) may not be achieved if connections are used in lieu of extended reinforcements.

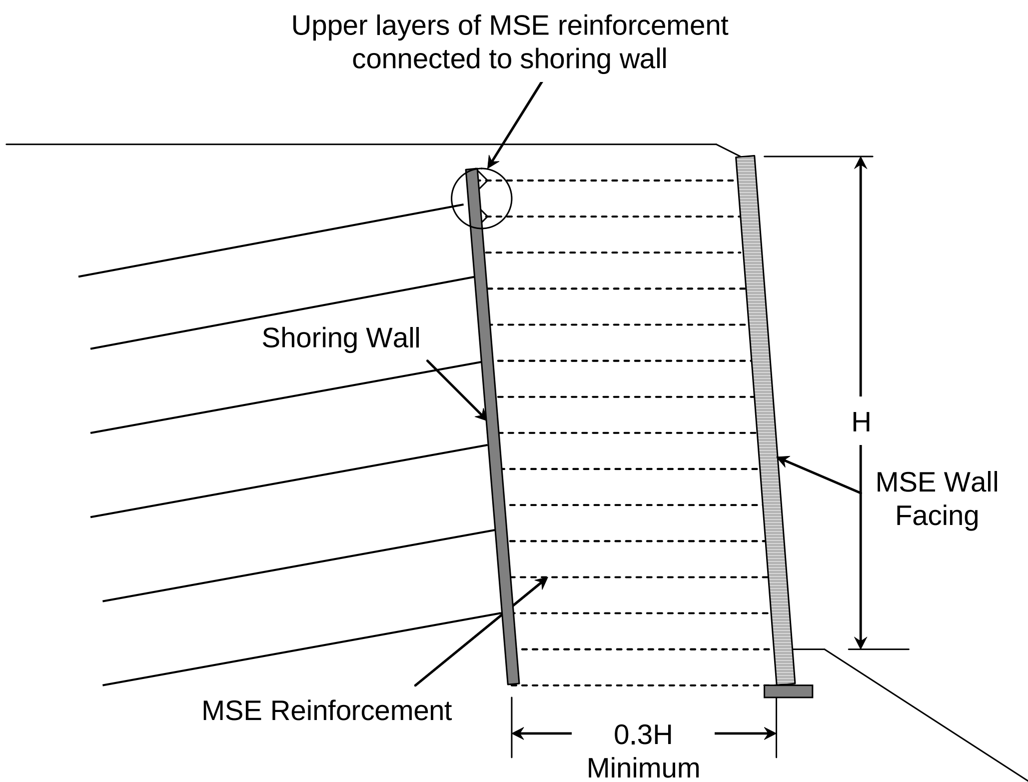


Figure 7. Diagram. Alternate proposed geometry for MSE wall component of an SMSE wall system.

Options for interface connections include two general types—mechanical and frictional. Several possibilities for connection of the shoring and MSE wall systems are summarized as follows:

- Frictional connection options – (1) wrapped-back MSE reinforcements, (2) stepped wall interface, and (3) MSE reinforcements bent upward at shoring interface. Figure 8 conceptually illustrates these frictional connection options.

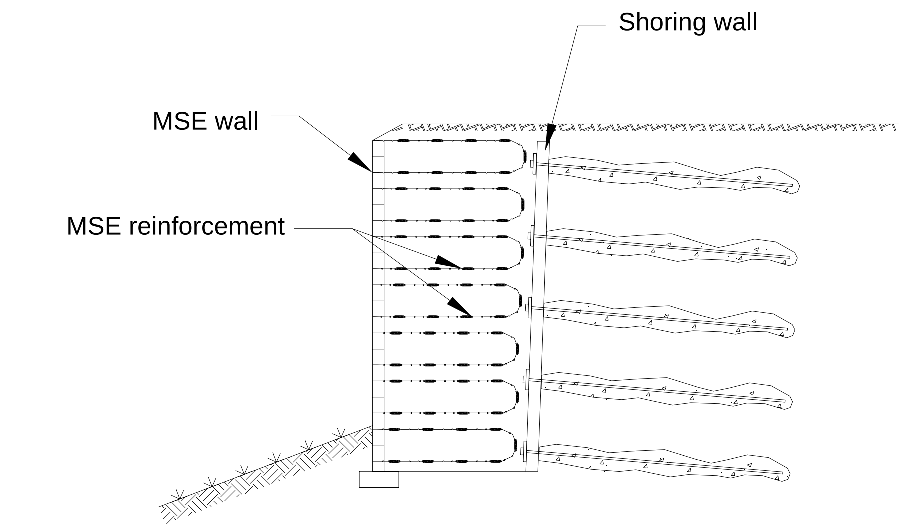
- Mechanical connection options – (1) connect MSE reinforcement layers to the shoring wall using bodkin joints or other means, and (2) install short MSE reinforcements near reinforcement levels in the shoring wall, and extend or overlap the reinforcement "tails" into the MSE wall component during MSE construction. Figure 9 conceptually illustrates these mechanical connection options.

Frictional connections are likely simpler to construct than mechanical connections. By wrapping the back of the MSE reinforcements as shown in figure 8, increased pullout resistance of the MSE reinforcements would result.(5) Centrifuge modeling (see appendix B) of wrapped-back MSE reinforcements indicated improved stability of the MSE mass compared to an unconnected SMSE wall system. Based on the geometry of a stepped wall interface, an increase in the shearing resistance along the interface is achieved. Construction of a stepped interface is further discussed in section 3.3.2. Mechanical connections require detailed design and construction oversight to ensure that the connections are constructed appropriately.

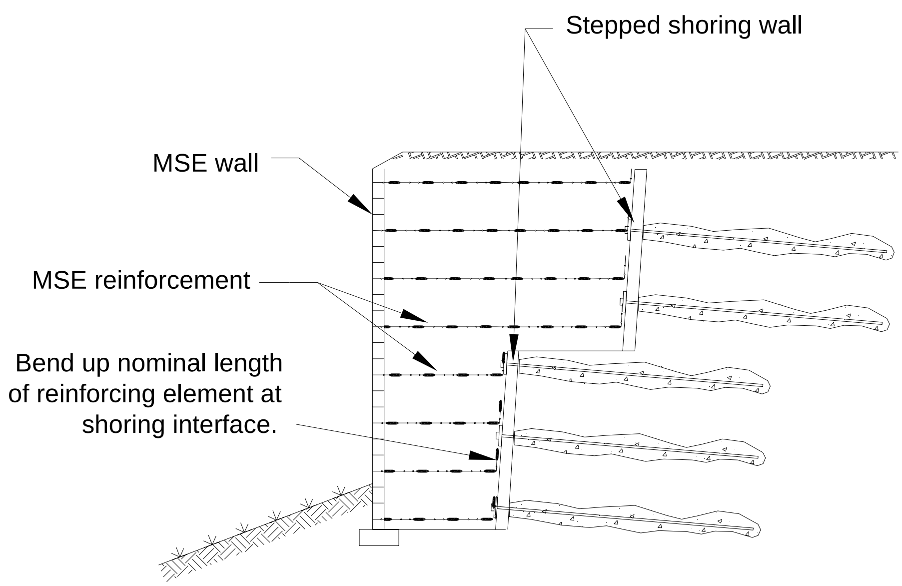
Foundation Embedment

Design toe embedment (i.e., the depth to the top of the leveling pad from the adjacent finished grade elevation) for the MSE wall component should be based on geotechnical design requirements for bearing capacity, global stability, and settlement. The embedment depths summarized in table 2 are commonly followed.(2) However, table 2 should not be a substitute for evaluating the geotechnical design requirements for bearing or global stability, but instead considered a starting point for the calculations.

The effects of frost heave, scour, proximity to slopes, erosion, and potential future excavation in front of the wall should be considered when designing the embedment depth.(1) For walls constructed adjacent to rivers and streams, the embedment depth should be a minimum of 0.6 m below the potential scour depth.(1)



A. Wrapped-back MSE reinforcements



B. Stepped shoring wall and reinforcements bent at shoring interface

Figure 8. Diagram. Frictional connection options for an SMSE wall system.

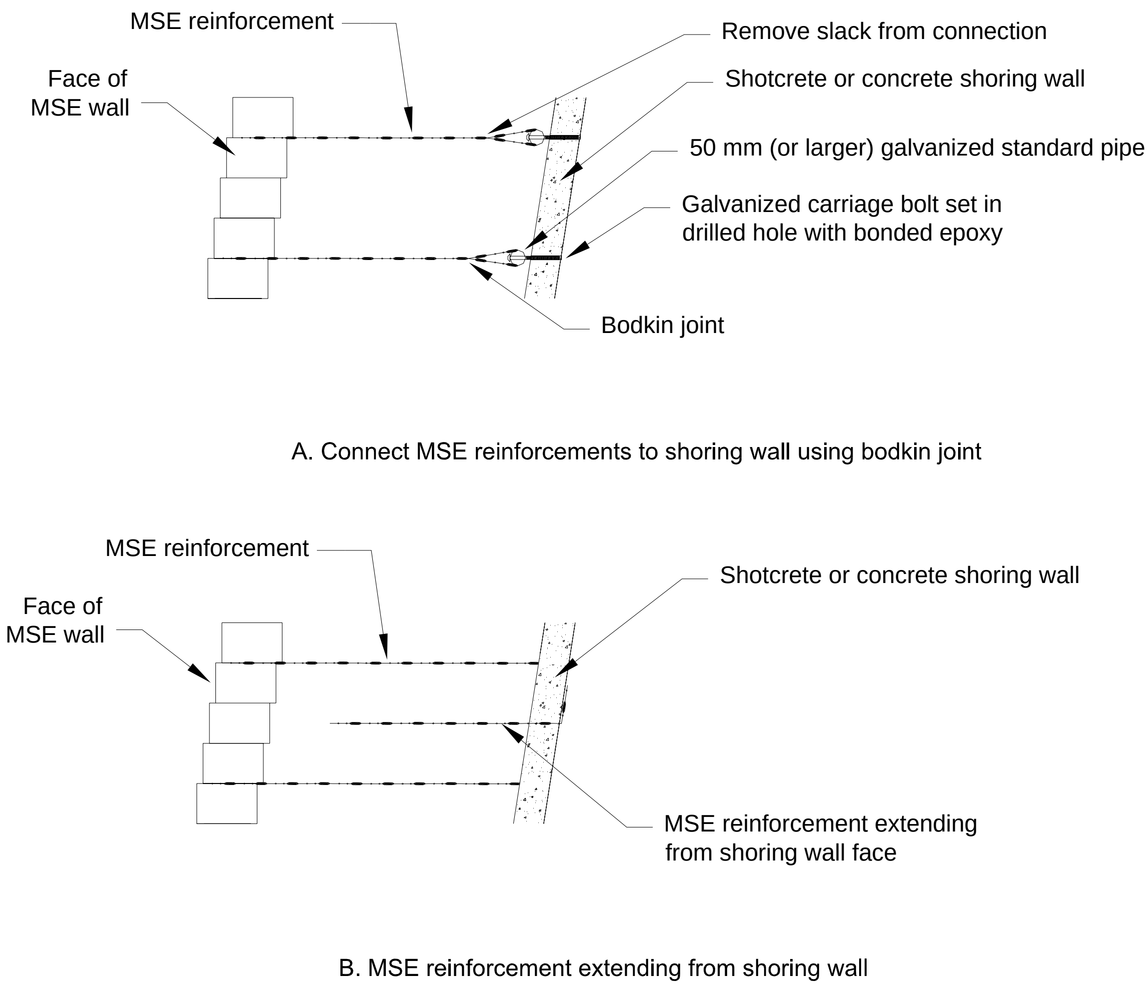


Figure 9. Diagram. Mechanical connection options for an SMSE wall system.

Table 2. Embedment depths (*d*) for MSE walls.(2)

Slope in Front of Wall	Minimum to Top of Leveling Pad[1]
Horizontal (walls)	*H*/20
Horizontal (abutments)	*H*/10
3H:1V	*H*/10
2H:1V	*H*/7
3H:2V	*H*/5

[1] *H* is the height of the MSE wall excluding embedment.

Geometry of MSE/Shoring Interface

The face of the shoring wall defines the geometry of the MSE/shoring interface. The shoring system, and hence the MSE/shoring interface, may be constructed at a batter, vertically, or stepped. Where shoring is necessary, the interface surface between the two wall systems will generally be steep or vertical. The wall designer should consider designing the shoring wall with a nominal batter (up to 10 degrees from vertical) to reduce the risk of tension crack development, as discussed previously in section 3.2. Another option, where adequate working room is available, is construction of a stepped interface to strengthen the system against shear failure along the interface, illustrated in figure 10. Qualitatively, offsetting the steps of the stepped shoring wall a small amount (i.e., by as little as 0.5 m) may increase the resistance of the SMSE wall system to instability along the interface. A slope (2H:1V or flatter) may be incorporated between shoring wall steps to nominally reduce the shoring wall area. Whether or not a batter or stepped geometry is employed, extension of the upper MSE reinforcements to a minimum length of 0.6*H* is recommended to mitigate tension crack development, as discussed previously in this report.

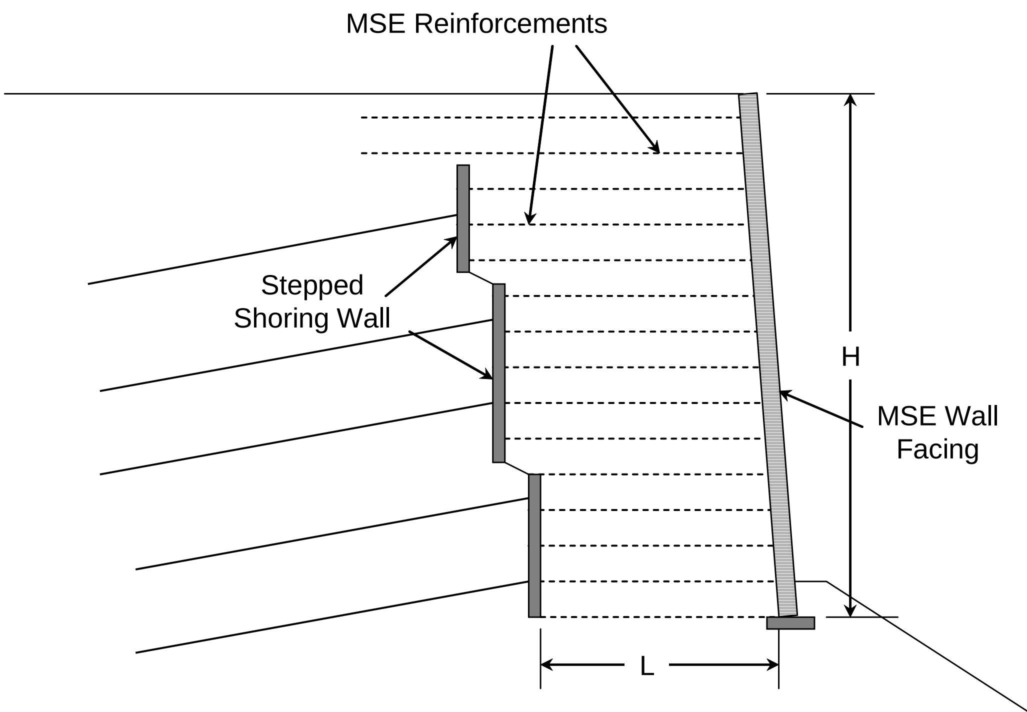


Figure 10. Diagram. Stepped shoring wall interface.

3.3.3 Drainage Considerations

Because the SMSE wall system is designed based on long-term performance of both the shoring wall and the MSE wall components, wall drainage provisions for both components are crucial. Drainage for the shoring component should be connected to the drainage system of the MSE component, or extended through the face of the MSE wall. Because the reinforced fill zone of SMSE walls is specified as free-draining granular material, drainage at the back of the MSE portion of the wall may not be required. Where modular block units or other relatively impermeable facing type is used, drainage directly behind the wall facing should also be incorporated. Figure 11 illustrates a concept for SMSE wall internal drainage (assuming a soil nail shoring wall) with an outlet for shoring wall drainage through the MSE component. For SMSE wall construction in areas with high groundwater levels, the engineer may consider a drainage blanket both behind and beneath the reinforced fill zone.

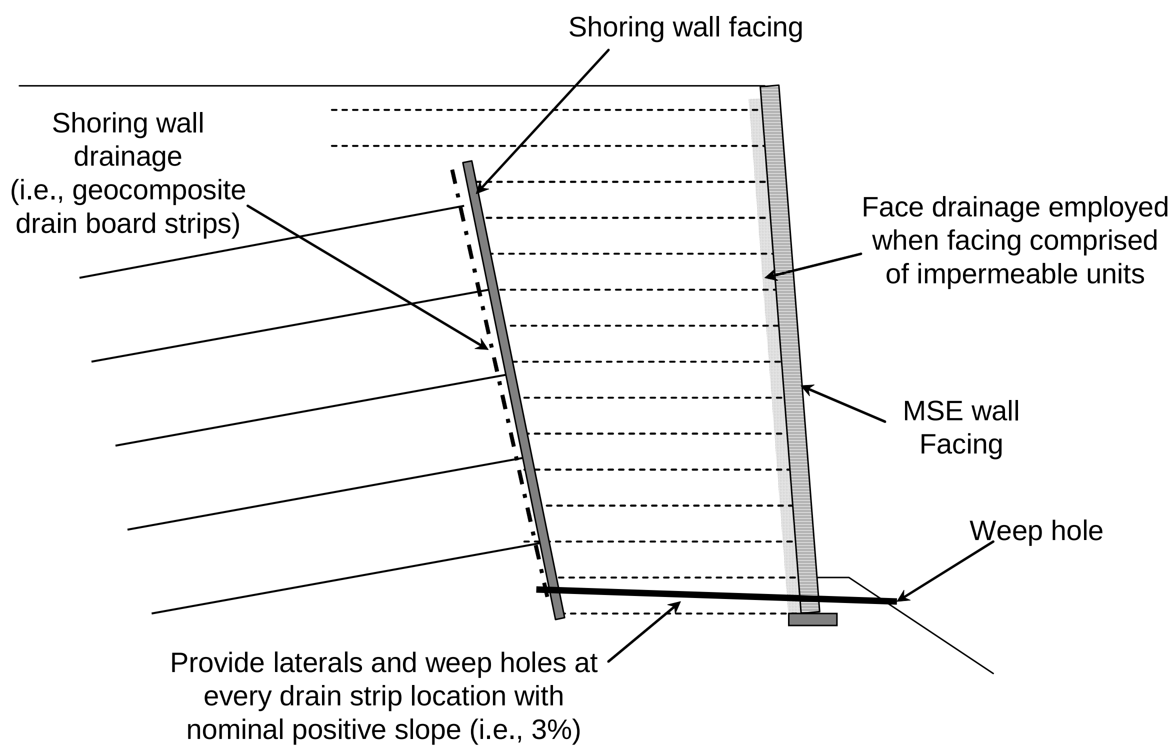


Figure 11. Diagram. Conceptual internal drainage for SMSE wall system.

Surface water infiltration into an SMSE wall system should be limited. This is particularly important for deicing chemicals on roadways which may cause degradation of steel reinforcements or connections. For MSE components with metallic reinforcements supporting roadways that are chemically deiced, an impervious geomembrane should be placed below the pavement and above the first row of reinforcements to intercept flows containing the aggressive chemicals.[1]