# CHAPTER 9 — CONCLUSIONS AND RECOMMENDATIONS

The design guidelines and recommendations presented in this report were developed based on results of a literature review (appendix A), centrifuge modeling (appendix B), field-scale testing (appendix C), and numerical modeling (appendix D). This chapter summarizes the conclusions of this report regarding SMSE wall system design, and presents recommendations for future research.

## 9.1 CONCLUSIONS

Based on the results of the research conducted and presented, a minimum MSE reinforcement length equivalent to 30 percent of the wall height, i.e., aspect ratio of 0.3, has been selected for design of SMSE walls, with a recommended within reinforcement length of 1.5 meters. Centrifuge modeling of SMSE wall systems indicated that aspect ratios on the order of 0.25 to 0.6 produced stable wall configurations, while 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 of 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 such walls are subject to low lateral earth pressures.

Centrifuge modeling indicated that SMSE walls with aspect ratios less than 0.6 exhibited deformation in the form of “trench” development at the shoring interface, indicative of tension cracking. Because trench development was not observed for models with aspect ratios of 0.6 or greater, these guidelines recommend that the upper two or more layers of geogrid extend to a minimum length of 0.6$H$ or 1.5 meters beyond the shoring wall, whichever is greater, to limit the potential for tension cracking at the interface. Additional constraints regarding the geometry of the overlapped layers and related guidance are provided in chapter 3.

Measurements of lateral earth pressures recorded at the shoring interface during field-scale testing imply that the pressures acting on the back of the MSE wall component are less than the theoretical active earth pressures. The design procedure presented is based on active earth pressure and considered conservative.

Based on the research, an analytical approach for design of the MSE wall component of an SMSE wall system is presented in chapter 5. This approach differs from traditional MSE wall design with regard to reinforcement pullout design. Conventional MSE wall design requires that each layer of reinforcement resist pullout by extending a nominal distance beyond the estimated failure surface.(2) In the case of an SMSE wall system, the lower MSE reinforcement layers (i.e., those that extend into the resistant zone) are designed to resist pullout for the entire “active” MSE mass. Additionally, external analysis of the MSE wall component includes evaluation of stability along the MSE/shoring interface, a feature that does not exist for a conventional MSE wall.

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.

The design recommendations specific to SMSE wall systems presented in this report are summarized in table 5.

**Table 5. Summary of SMSE wall system design recommendations.**

| Design Feature or Requirement | Recommendation |
|---|---|
| Minimum aspect ratio, $\alpha$ | 0.3 |
| Minimum reinforcement length | 1.5 m |
| Maximum reinforcement vertical spacing, $s_v$ | 0.6 m |
| Internal design, pullout | Specific to SMSE walls systems, per section 5.3 |
| Internal design, reinforcement rupture | Generally follows traditional approach |
| Factor of safety against reinforcement pullout, $FS_p$ | 1.5 for aspect ratios greater than 0.4<br>2.0 for aspect ratios less than or equal 0.4 |
| Shoring wall batter | 1H:14V or greater |
| Upper two or more reinforcements | Extend to length of 0.6*H*, or 1.5 m beyond shoring wall, whichever is greater |
| Reinforced backfill | High quality granular fill, section 3.3.1 |
| Shoring wall construction | Permanent structure |
| Shoring wall design | Potentially reduced factors of safety (i.e., temporary stability factors of safety) |

## 9.2 RECOMMENDATIONS

This section provides recommendations with regard to implementation of SMSE wall design and construction, and SMSE wall monitoring. Future research of SMSE walls is recommended to improve and expand potential applications.

### 9.2.1 Implementation

CFLHD may commence with design and construction of SMSE wall systems using the guidelines and recommendations presented in this report. Until satisfactory performance of SMSE walls designed using these guidelines is adequately established, performance monitoring should be implemented with a scope that is above and beyond that of a traditional MSE wall. Recommendations for wall monitoring are discussed in section 9.2.3.

### 9.2.2 Wall Monitoring

Until satisfactory performance is confirmed for SMSE walls designed using the guidelines presented in this report, a monitoring program should be established for each SMSE wall constructed. The scope and level of instrumentation and monitoring will be developed on a project-to-project, and perhaps wall-by-wall, basis.

Evaluation of how SMSE walls function, not just how they perform, is important as FLH starts to deploy them on projects. This information will allow FLH to optimize the design and utilization of the wall type. Monitoring for wall function is more difficult and costly than monitoring for wall performance and FLH should look for opportunities where this more extensive monitoring program can be implemented. A monitoring program that evaluates how the SMSE wall functions, as well as how well it performs, should consider the following components:

- Bonded-resistance strain gages installed on the MSE reinforcements to evaluate the local stress and strain distribution in the wall.

- Mechanical extensometers installed on the MSE reinforcements to evaluate the global strain and stress state in the reinforcement. These may be installed in conjunction with strain gages to provide redundancy.

- Inductance coil strain gages placed between MSE reinforcing layers to evaluate lateral strains in the reinforced soil mass.

- Lateral earth pressure cells installed on the face of the shoring wall to measure lateral pressures at the back of the reinforced fill.

- Inclinometers installed at the face of the MSE wall and just behind the face of the shoring wall to measure horizontal movement of each of the wall components.

- Monitoring of vertical and horizontal movements of the MSE wall facing by conventional optical surveys.

- Monitoring vertical movement of the MSE wall portion by using settlement sensing devices installed at the base of the wall.

- Horizontal earth pressure cells installed at various locations along the base of the MSE wall portion (i.e., near shoring, near facing, and at midpoint) to measure vertical pressures at the base of the MSE wall and evaluate the presence of arching.

Several things to consider when designing the instrumentation program include:

- Sensitivity - The instrumentation should be sensitive over a wide range of strains (i.e., large during construction, and very small following construction).

- Strain compatibility - The gages and their respective attachment methods must be compatible with the type of reinforcement material.

- Redundancy - The instrumentation program should provide sufficient redundancy to explain anomalous data.

- Quantity - A sufficient number of instruments spaced preferentially to identify areas of high stress should be provided.

- Monitoring intervals - The monitoring program should include continuous monitoring during construction, establishment of post-construction baseline readings, and monitoring at a regular interval (i.e., monthly or quarterly) until sufficient data to confirm performance of the wall system is achieved.

In addition to monitoring of wall instrumentation, observational monitoring is recommended. This includes visual inspection of the surface (i.e., pavement) above the SMSE wall for tension cracking and observation of the wall facing for signs of distress. Observational monitoring should be conducted at least as frequently as the optical survey or measurement of inclinometers. Other instrumentation should be connected to a data logger(s) with recording of continuous or incremental measurements.

Several of the benefits associated with the instrumentation and monitoring program summarized above include measurement of stresses and strains within the MSE reinforcements, lateral pressures acting on the MSE wall component, and vertical pressures and deformations at the base of the MSE wall component in addition to monitoring deformation of the MSE wall facing and potential outward deflection of the shoring wall component. Implementation of this full instrumentation program provides data suitable for further evaluation of how SMSE walls work. Such an extensive monitoring program is not substantiated for most projects, and may only be employed on a few. For most SMSE walls a lesser program should be implemented.

For performance monitoring of an SMSE wall system, monitoring of deformations is more beneficial than monitoring of stresses, and the cost of deformation monitoring is generally quite less than monitoring of stresses. For instance, strain gages and pressure cells that provide data regarding stress and strain distributions within the reinforced soil mass are quite costly and require redundancy.

In order to monitor performance, with the goal of measuring deformations, a minimum monitoring program should consider the following:

- Inclinometers installed behind the face of the shoring wall portion and behind the face of the MSE wall portion (minimum of two inclinometers per wall section).

- Survey monuments at the top face of the MSE wall portion on a nominal spacing of 8 meters, with a minimum of three monuments per wall section (one installed at each end of the wall and one near the midpoint), or optical surveys of MSE wall facing deformation.

- Observational monitoring which includes visual inspection of the surface above the wall for tension cracking, and visual inspection of the wall facing for signs of distress.

This minimum monitoring program should be implemented with measurements recorded at completion of wall construction (i.e., baseline), and quarterly thereafter for a minimum of one year.

### 9.2.3 Future Research

Evidence collected during preparation of these guidelines suggests that the lateral pressures acting on the MSE wall component of an SMSE wall system are less than active earth pressures due to the stabilizing benefits provided by the shoring system. Lateral earth pressures were measured during the field-scale testing (appendix C). Generally, the lateral earth pressures were less than theoretical Rankine active earth pressures. The field-scale test indicated that the lateral pressures near the top of the wall were considerably higher for the connected system than they were for the unconnected system. Assumptions were stated with regard to possible tension crack development for the unconnected wall system, and transfer of load via the reinforcements for the connected wall system. The relationship between connected versus unconnected wall systems should be further investigated, though indications are that the connected system provides little benefit for walls constructed in accordance with these guidelines.

The goal of the numerical modeling was to verify the results of the field-scale test, and provide additional insight into the results of the instrumentation. This goal was accomplished, as discussed in appendix D. Numerical modeling also provided insight to the degree of lateral pressures acting on the MSE wall component of an SMSE wall system, indicating that the lateral pressure increases with increasing surcharge load. The degree or level of reduction of the lateral pressure due to the shoring wall was not clearly quantifiable from either the field-scale test or numerical modeling, and further quantification of the lateral stresses is recommended.

Numerical modeling is a powerful tool which may used to evaluate additional parameters with regard to SMSE wall systems, including one or more of the following:

- Fully- and partially-connected versus unconnected SMSE wall systems.

- Extension of upper layers of geogrid for unconnected SMSE wall system.

- Shoring wall geometry (i.e., stepped interface).
- Shoring wall type with regard to rigidity and pressures acting on the MSE wall mass.
- Varying aspect ratios from 0.25$H$ to 0.5$H$.

The shoring wall component was modeled as a rigid unyielding member in the research conducted for this report. However, the shoring wall will exhibit some deformation which was not quantified in the research. Soil nail walls, for instance, are a relatively flexible system and require small deformations in order to mobilize their strength. The effect of a flexible shoring wall on the MSE wall component could be the subject of additional investigation, as mentioned above with regard to numerical modeling. However, this may better be accomplished by conducting ongoing monitoring of constructed SMSE wall systems.