APPENDIX A — LITERATURE REVIEW

A mechanically stabilized earth (MSE) wall behaves as a flexible coherent block able to sustain significant loading and deformation due to the interaction between the backfill material and the reinforcement elements. The American Association of State Highway and Transportation Officials (AASHTO) and Elias et al. design methodologies for MSE walls are based on internal and external stability analyses using limit equilibrium methods.[1,2] The Federal Highway Administration (FHWA) has adopted Elias et al. as their current guideline for MSE wall design.[2] The current design methodologies for MSE walls do not directly take connection strength, secondary reinforcement layers, or foundation stiffness into consideration. Current design methodologies also do not allow for reduction in lateral earth pressures on the MSE mass due to shoring construction, when the shoring will be abandoned in place or incorporated into the final design of a composite wall system. However, current design methodologies do consider stiffness of MSE reinforcements, where the internal lateral earth pressure coefficient (K_r) is higher for stiffer (i.e., steel) reinforcements than for extensible (i.e., geosynthetic) reinforcements.

A literature review was conducted to evaluate various components of MSE wall design with specific emphasis on shored construction of MSE walls, including: reinforcement spacing, reinforcement length, non-rectangular reinforcement geometry, and internal design loading assumptions. An additional literature review identified case histories of full-scale testing on MSE walls to assist in planning the field-scale testing for this study.

A.1 REINFORCEMENT SPACING

The internal behavior of a reinforced soil mass depends on a number of factors, including the "soil-reinforcement ratio," or reinforcement spacing. In many cases, the internal stability of the MSE wall controls the wall design due to the large reinforcement length specified in preliminary sizing of the wall using current public sector design methodology (i.e., 0.7*H*).

Collin conducted the first finite element modeling analysis on MSE walls, evaluating the effects of reinforcement stiffness on lateral earth pressure.[36] Vulova conducted two-dimensional finite difference modeling to investigate the behavior of MSE walls with reinforcement spacings ranging from 0.2 to 1.0 m.[37] Vulova found that internal failures, characterized by critical slip surface development through the reinforced soil, occur only for large reinforcement spacings and that internal stability is a function of reinforcement strength and reinforcement pullout.

A.2 REINFORCEMENT LENGTH

The National Concrete Masonry Association (NCMA) design manual used for design of MSE walls in the private sector requires a minimum reinforcement length to wall height ratio (*L*:*H*) of 0.6.[11] Design manuals used for design of MSE walls in the public transportation sector require a minimum reinforcement length to wall height ratio of 0.7.[1,2] Criteria similar to Elias et al. and AASHTO are the standard of practice in Europe and Asia. (See references 1, 2, 6, and 38.) In these regions, a minimum aspect ratio of 0.7 is used for standard applications and 0.6 is used for low lateral load applications with a minimum length of 3 m.(6,38) Because current design practice involves designing each component of a shored MSE (SMSE) wall system completely independent of the other, the reinforcement length prescribed by these design guidelines are most likely conservative. Reinforcement lengths less than 60 percent of the wall height (0.6*H*) have been reported in the literature, as discussed below.

A.2.1 Geosynthetic-Reinforced Soil Retaining Walls

In the 1980s, researchers in Japan constructed a geosynthetic reinforced soil wall using a rigid facing with reinforcement lengths considerably less than 0.6*H*. (See references 39, 40, 41, and 42.) The geosynthetic-reinforced soil retaining wall (GRS-RW) system uses a full-height rigid facing which is cast-in-place by staged construction procedures, geosynthetic reinforcement, and reinforced fill consisting of low-quality onsite soils. (See references 39, 40, 41, and 42.)

Of particular interest is the small aspect ratio (i.e., reinforcement length versus wall height) that has been employed in the GRS-RW system. Researchers in Japan constructed six full-scale walls and conducted three series of model laboratory tests on reinforced embankments with reinforcement lengths approximately 30 percent of the wall height (i.e., 0.3*H*).(40,41) The two main features that allowed these systems to use short reinforcements included the use of planar geosynthetics and the use of a continuous rigid facing. Figure 30 illustrates the staged construction procedure for GRS-RW systems.

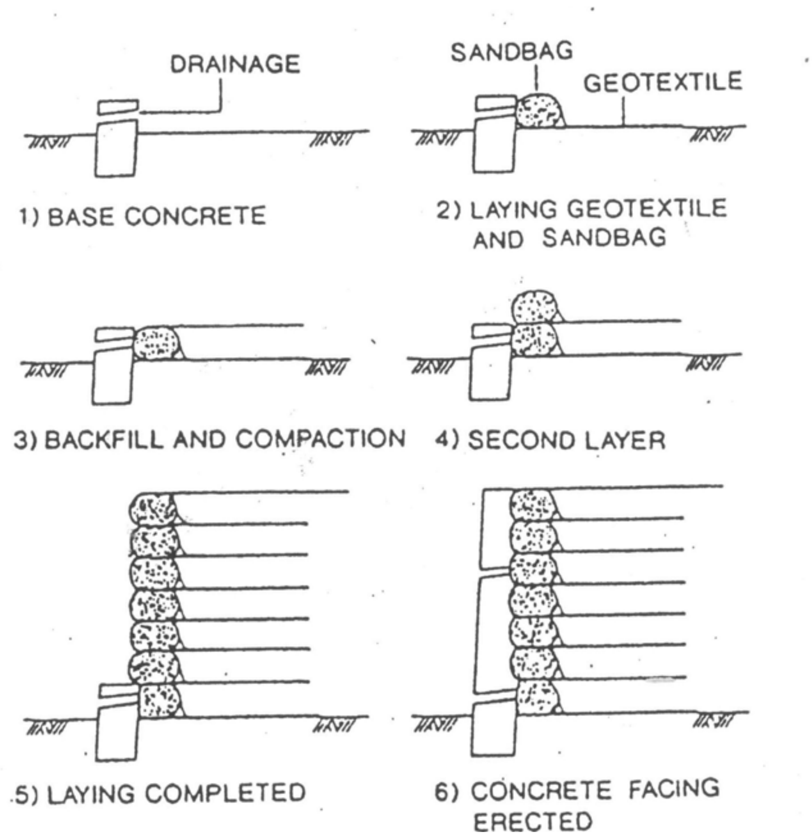


Figure 30. Illustration. Staged construction procedures for the GRS-RW system.(43)

Tatsuoka et al. concluded that the use of planar geotextile sheets reduce the required anchorage length by increasing the contact area with the backfill, as compared to the use of metal reinforcing strips.(40) Planar geotextile sheets may consist of geogrid for use in cohesionless or cohesive soil backfill. A composite of non-woven and woven geotextiles, for instance, may be suitable for a backfill containing cohesive soils to facilitate drainage and to ensure high tensile capacity.(40) Because geosynthetics tend to have a lower tensile strength than steel reinforcement, more layers of reinforcement are used in the GRS-RW system than in traditional MSE walls.

A continuous rigid facing (i.e., reinforced concrete placed directly over a geosynthetic-wrapped wall face) increases the stability of the wall, reduces the lateral and vertical deformation at the wall face, and reduces settlement of the wall backfill by enabling the reinforced zone and the facing to act together.(40) One of six full-scale tests constructed by researchers in Japan used a non-rigid facing and exhibited considerably more deformation than those models constructed with continuous rigid facing.(40) Tatsuoka et al. suggests that overturning may be the most critical mode of failure for an MSE wall with short reinforcement lengths (i.e., $0.3H$), where sliding typically governs for conventional MSE walls (i.e., $0.7H$).(40)

Tateyama et al. designed a geosynthetic-reinforced retaining wall with reinforcement lengths of approximately $0.45H$, designed for a partial factor of safety of 1.5 for pullout failure of the reinforcement.(42) The wall was constructed to an average height of 5 m and a total length of 930 m and was subjected to dynamic loading by trains passing above the wall. Wall behavior was monitored for a period of about 1.5 years, and reported to perform well.

A.2.2 Constrained Reinforced Fill Zones

A design-and-analysis method for reinforced soil retaining walls where the extent of the reinforced fill zone is constrained by the presence of a rock or heavily over-consolidated soil outcrop making conventional MSE wall construction with reinforcements of $0.6H$ impractical is provided by Lawson and Lee.(5) For this method, they state that "constraining the extent of the reinforced fill zone reduces the internal stability of the reinforced segmental block wall by preventing full dissipation of tensile stresses in the geogrid reinforcement within the reinforced fill zone."(5) Similar to a shored MSE wall, the rigid zone is assumed to be inherently stable and therefore does not impart any stresses onto the reinforced soil block. Within the constrained reinforced fill zone, the full active failure wedge is unable to develop because of the relative close proximity of the rigid zone behind the reinforced fill. Lawson and Lee evaluated the effect of the geometry of the constrained reinforced fill zone on the magnitude of horizontal stresses acting on the wall face, P_h, according to the following equation:

$$P_h = \frac{1}{2} K \gamma H^2 \qquad \textbf{Equation A.1}$$

For walls with aspect ratios greater than 0.5, the theoretical active wedge can fully develop within the granular fill zone and hence K is equal to K_a. However, for aspect ratios less than 0.5, the full active wedge cannot develop fully and the magnitude of K was observed to decrease for decreasing aspect ratios.(5) Lawson and Lee propose dissipation of residual reinforcement tensions by either connecting the geogrid reinforcements to anchors or nails inserted into the rigid zone, or by extending the geogrid reinforcement in the form of a wrap-around at the rear of the reinforced fill zone.[5]

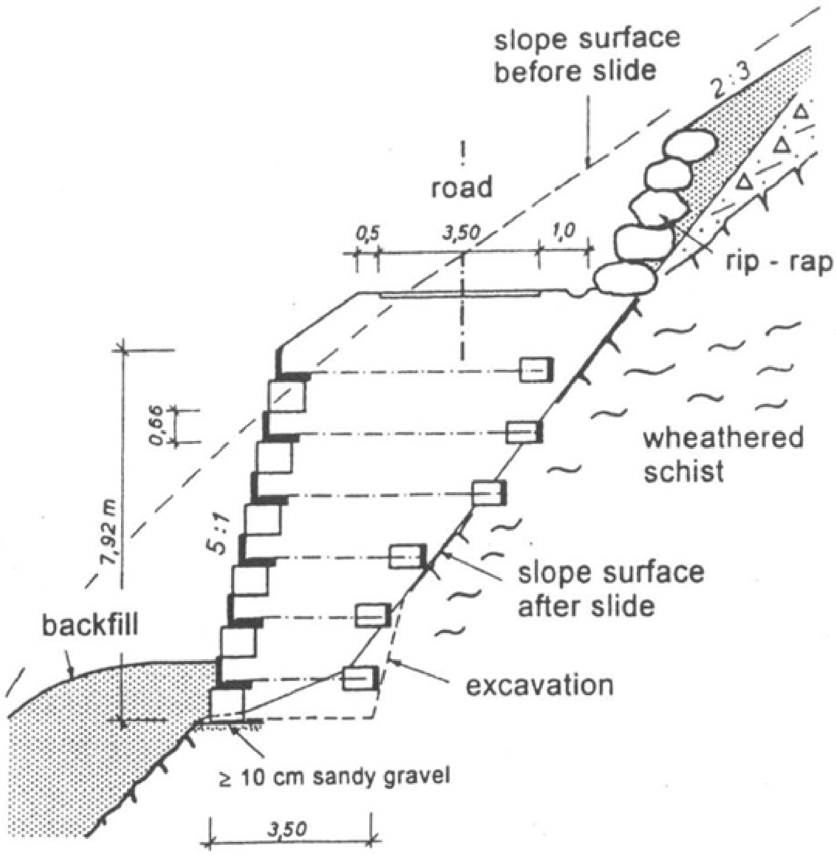
A.2.3 Other Constructed Cases of Short Reinforcement Lengths

Other cases of MSE walls constructed using short reinforcements (less than 0.6*H*) are found in the literature. However, no studies for shored MSE walls using short reinforcement lengths have been identified, except for the case where standard MSE block units have been used as aesthetic facing (i.e., veneer) for soil nail walls.

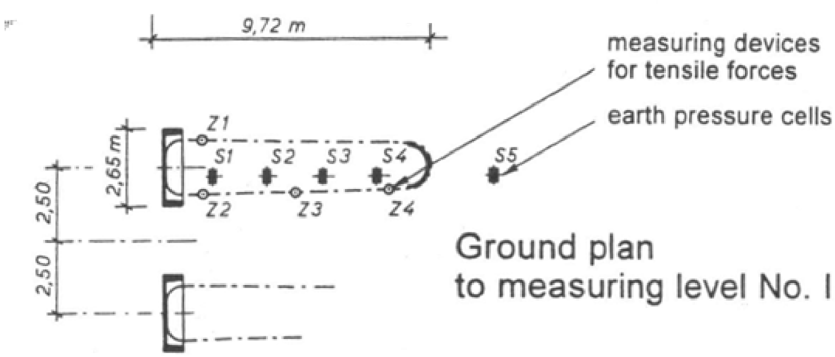
A common alternative to the GRS-RW wall system is a Reinforced Earth® Wall using metallic reinforcements with segmental facing. Such walls are constructed using reinforcement lengths as low as 0.45*H*. A study conducted by Terre Armee International showed that these wall systems may be stable with reinforcement lengths ranging from 0.7*H* to 0.4*H*.[44]

Another type of wall system employing short reinforcements is a multi-anchored retaining wall with geosynthetic loop anchors.[45] A cross section of a multi-anchored wall is illustrated in figure 31. The main concept of this type of wall is that the reinforcement extends beyond the failure wedge, but the anchorage length may be significantly reduced because the reinforcement is looped in a manner that essentially restrains the failure wedge. This looping increases the pullout resistance of the MSE reinforcements. Figure 31 illustrates a wall used to stabilize a steep slope after a landslide. The aspect ratio for this wall system is a minimum of 0.44*H* at the base of the wall, increasing towards the top of the wall.[45]

Lin et al. describe a wall similar to an SMSE wall constructed with a multi-nailing system combined with soil reinforcement.[46] This system was chosen in an attempt to reduce the required reinforcement length where the wall was comparatively tall (39.5 m) and would have required 24-meter-long MSE reinforcements using the criterion developed for the private sector (0.6*H*). Consequently, the wall designer elected to replace a portion of the reinforcing element length with rock nails to reduce the amount of required excavation by 80 percent. The design involved stabilization of the vertical slope with rock nails and tiered construction of an MSE wall in front of the stabilizing shoring wall, as illustrated in figure 32. The MSE walls employ reinforcement lengths of 1.5 m and each wall section was 8 m high, resulting in an aspect ratio of 0.19. The MSE wall facing consists of steel mesh which was attached to the nails of the shoring system using galvanized cables. The MSE walls in this application were not designed to carry vertical loading, but instead constructed for aesthetic purposes.



A.



B.

Figure 31. Illustration. Profile of a multi-anchored wall (A) and plan view of the reinforcement (B).[45]

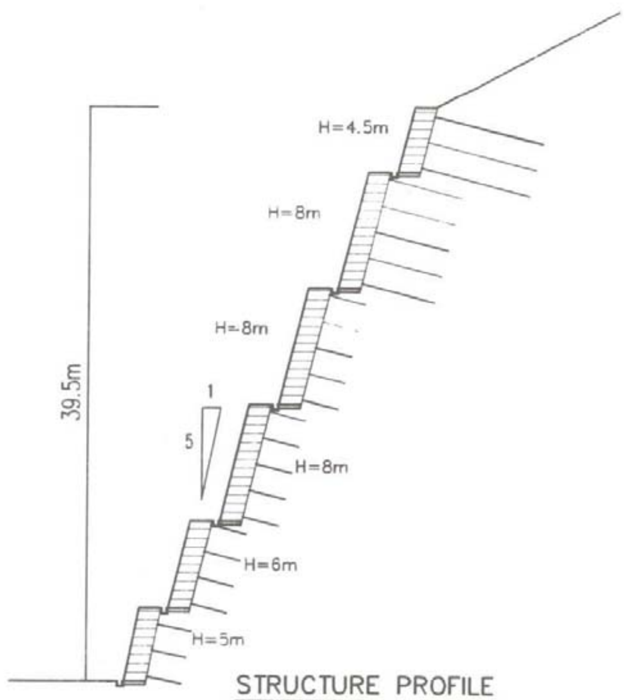


Figure 32. Illustration. A multi-nailing shoring system combined with MSE construction.[46]

A.2.4 Numerical Analyses Evaluating Short Reinforcement Lengths

Numerical studies have been reported which analyze short reinforcements in MSE walls.[37,47] A study by Vulova, though focusing on the affect of MSE reinforcement spacing, used *Fast Lagrangian Analysis of Continua* (*FLAC*), a finite difference numerical analysis program, to investigate MSE reinforcement length among other variables.[37,48] The models were simulated by constructing one layer at a time with a fixed length, where the addition of successive layers resulted in decreasing the aspect ratio of the wall until yielding and wall collapse occurred. The minimum aspect ratio achieved in this study was 0.17 with a reinforcement spacing of 0.2 m; the model failed due to overturning. An aspect ratio of 0.19 was achieved with a reinforcement spacing of 0.4 m, with this model failing in a compound mode with the failure surface developed through the retained fill as well as through the reinforced fill. In both cases, the stresses in the soil and in the reinforcements were found to be largest nearer to the facing than towards the end of the reinforced zone, increasing the tendency for overturning.[37] This was observed in the field-scale test performed for this report (appendix C) where the vertical stresses measured at the base of the MSE wall near to the MSE facing were approximately 20 percent higher than the vertical stresses measured near the shoring wall. One reviewer of Vulova's research asserted that both models failed in an overturning mode, though a shear surface was able to develop for the model with an aspect ratio of 0.19 due to the larger reinforcement spacing, which in turn appeared to lead to a compound failure.[49]

Another numerical study involving finite element analyses showed that the behavior of an MSE wall underwent changes due to reduced reinforcement length, but remained quite similar as long as the length of the reinforcements were generally kept above 0.4*H* to 0.5*H*.[47] This numerical study was confirmed by conducting full-scale testing on an MSE wall constructed with short reinforcing strips (0.48*H*) loaded to a test pressure of 840 kPa. The full-scale test wall exhibited little distress at this high load.[47] Similar to Vulova, Bastick concluded that the maximum tensile forces developed in the reinforcements near the top of the wall are slightly closer to the facing than the usual theoretical position of 0.3*H* for an MSE wall employing inextensible reinforcements.[37, 47] The field-scale test performed for this report (appendix C) employed extensible reinforcements, so this conclusion could not be further evaluated. However, the maximum tensile forces in the MSE reinforcements were observed to occur near the top of the wall and closer to the wall facing than the theoretical location of the Rankine active failure wedge.

A.2.5 Summary

Various attempts have been reported in the literature to minimize the length of the reinforcements in MSE structures, illustrating the need for additional research in this area. To date, the minimum reinforcement length reported to have been successfully constructed in a permanent structure was by Japanese researchers for GRS-RW systems, with an aspect ratio of 0.3. All of the examples of short MSE reinforcements presented in this report take advantage of low lateral earth pressures, similar to that developed within an SMSE wall. Centrifuge modeling, presented in appendix B, was conducted to investigate this phenomenon with regard to SMSE walls and short reinforcements where the lateral earth pressures are greatly reduced due to the presence of a shoring system.

A.3 NON-RECTANGULAR REINFORCEMENT GEOMETRY

For fill-side retaining wall construction on sloping or steep terrain, temporary excavations are typically required for construction of the reinforced fill structure. In these situations, use of a non-rectangular reinforcement cross section (or stepped wall) may prove beneficial due to the reduction in the required excavation size and/or elimination of temporary shoring wall construction.

A.3.1 North American Practice

Elias et al. presents design procedures for the design of MSE walls utilizing uneven reinforcement lengths, or non-rectangular geometry.[2] The manual states that such reinforcement geometry should only be considered if the base of the MSE wall is founded on rock or competent soil; competent soils are defined as materials which will exhibit minimal post-construction settlements.[2] For weak foundation materials, ground improvement prior to MSE construction may be considered viable, allowing for use of nonstandard reinforcement geometries. Several foundation improvement options for MSE wall construction on weak foundations are found in the literature.[11]

The simplified design guidelines outlined in Elias et al. for walls with uneven reinforcement lengths include:

- Representing the wall by a rectangular block (L_o, H) with the same area as the non-rectangular cross section for external stability calculations (figure 33).
- Assuming that the maximum tensile force line is the same as in rectangular walls.
- Assigning a minimum base length (L_3) greater than or equal to $0.4H$, with the difference in length in each zone being less than $0.15H$.
- Dividing the wall into rectangular sections for each of the different reinforcement lengths for calculating internal stability or pullout.[(2)]

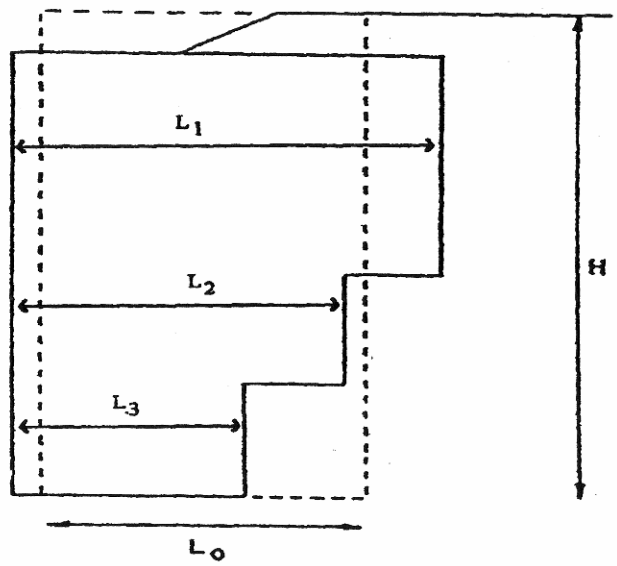


Figure 33. Diagram. Dimensioning for MSE wall with variable reinforcement lengths.[(2)]

Thomas used finite element methods to model MSE retaining walls having a truncated base, concluding that the quality of foundation and backfill materials has a significant influence on the performance of MSE retaining walls with a truncated base.[(50)] A forensic study conducted by Lee et al. on a series of failed retaining walls founded on rock with rock forming the backslope for the lower reinforcements concluded that the resistance against translation (or sliding) failure is reduced by using a stepped MSE cross section due to the smaller base area.[(51)] This study further 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 encourages the formation of arching above the reinforcements, resulting in design calculations that likely overestimate the resistance to pullout.[(51)]

A.3.2 European Practice

The United Kingdom considers two types of non-rectangular cross sections: (1) a stepped wall, employing longer reinforcements at the bottom, and (2) a trapezoidal wall, employing shorter reinforcements at the bottom.[38] For the purpose of this discussion, the trapezoidal wall case is considered. The British Standard BS 8006 design manual for MSE walls states that walls with trapezoidal cross sections should only be considered where foundations are formed by excavation into rock or other competent foundation conditions exist.[38] For the case of a trapezoidal wall, BS 8006 prescribes a minimum length of $0.4H$ for the lower reinforcing members, with $0.7H$ for the upper reinforcements.[38] This guideline corresponds closely to that presented in Elias et al.

Bastick performed a full-scale test on a wall with a non-rectangular cross section. The trapezoidal cross section had longer reinforcements near the top of the wall, with shorter reinforcements at the base.[47] The reinforcement lengths were approximately $0.48H$ (for the similar rectangular section). Results of this study were presented earlier in section A.2.3.

A.3.3 Asian Practice

Hong Kong's Geoguide 6 design manual for MSE walls states that reinforced fills constructed on sloping rock foundations are often constructed as stepped walls.[6] When such construction is conducted, the possibility of soil arching at the base of the structure associated with the geometry of the steps in the foundation profile must be considered (i.e.,. $s_v < \gamma H$).[6] Reduced development of vertical pressure on the back portion of the reinforcing elements may result from the effects of soil arching, causing internal compression of the reinforced fill adjacent to the foundation steps.[6] By limiting the size of the steps, arching effects may be reduced [6]. In general, the design guidelines outlined in Geoguide 6 are the same as those outlined in Elias et al.[2, 6]

A.4 DESIGN EARTH PRESSURES

A.4.1 North American Practice

The NCMA and Elias et al. design guidelines use different approaches to estimate lateral earth pressures.[11, 12] Coulomb earth pressure theory is used for internal and external stability evaluation according to NCMA, while the FHWA guidelines use Rankine theory for internal stability and Coulomb theory for external stability.

For internal design, the lateral earth pressure coefficient K_r is determined by applying a multiplier to the active earth pressure coefficient, K_a. The ratio of K_r/K_a is evaluated based on the type of reinforcing and the depth below the top of the wall. For geosynthetic reinforcing, the ratio of K_r/K_a is equal to unity. Therefore, K_a is used for internal design with geosynthetics (excluding polymer strip reinforcement). For internal design of retaining walls with welded wire mats, the ratio of K_r/K_a is as much as 2.5 at the top of the wall depending on the type of reinforcing element used, reducing to 1.2 at a depth of 6 m and below. It should be noted that this method assumes that the vertical stress in the wall is equal to the weight of the overburden soils, conservatively neglecting surcharge pressures, temporary live loads, etc. It should be further noted that this method does not account for potential arching effects at the back of the wall, which may be observed where shoring and short MSE reinforcements are applied. However, the results of field-scale testing of a shored MSE wall with short MSE reinforcements (appendix C) indicated that at low surcharge pressures the vertical stress in the wall is equivalent to the weight of the overburden soils. As such, arching may be considered negligible at low loadings.

A.4.2 European Practice

For internal design of MSE walls, the British Standard BS 8006 discusses two methods: the tie-back wedge method and the coherent gravity method.(38) Comparison of European methods to those discussed in chapter 5 indicates that MSE walls are designed very much the same in the U.S. as they are elsewhere in the world.

The tie-back wedge method assumes active earth pressures (K_a) for design. The coherent gravity method uses a different earth pressure distribution, as follows:

$$K = K_0\left(1 - \frac{z}{z_o}\right) + K_a\left(\frac{z}{z_0}\right) \text{ for } z \le z_o \le 6 \text{ m} \qquad \textbf{Equation A.2}$$

$$K = K_a \text{ for } z > 6 \text{ m} \qquad \textbf{Equation A.3}$$

In these equations, K is the earth pressure used in the wall design, K_o is the at-rest earth pressure, and z is the depth of the reinforcement level measured from the top of the wall. In general, the distribution of lateral earth pressures within the reinforced block is considered to vary from the at-rest state (K_o) to the active state (K_a) in the upper six meters of the structure, and is considered to be entirely in the active state below 6 meters.

The tie-back wedge method is recommended for walls where the short term axial tensile strain exceeds one percent (i.e., polymeric reinforcing). The coherent gravity method is recommended where the short-term axial tensile strain is less than or equal to one percent (i.e., steel reinforcements).

A.4.3 Asian Practice

The Hong Kong Geoguide specifies the same design earth pressures as the British Standard, further indicating that the determination of design earth pressures for MSE walls is relatively consistent around the world.(6,38)

A.5 FULL-SCALE TESTING OF MSE WALLS

Instrumentation programs conducted on full-scale MSE walls were reviewed prior to developing a field-scale testing program (appendix C). This section provides a summary of these testing programs.

Liang and Almoh'd instrumented a 15.8-m high MSE wall bridge abutment in Ohio with point bearing piles located approximately 0.9 m behind the wall facing to transfer bridge loads to the subsurface strata.(52) Their instrumentation program focused on the measurement of axial forces in the reinforcement, vertical earth pressures at the base of the reinforced soil mass, lateral earth pressures acting on the wall facing, and deflection of the wall facing by employing vibrating wire strain gages, interface pressure cells, vertical pressure cells and survey methods. Field measurements of reinforcement working forces were compared to the FHWA approach and to the load and resistance factor design (LRFD) method, and found to more closely approximate the LRFD method. Vertical pressure measurements at the base of the reinforced zone showed large variations from the predictions of the three distribution methods: Meyerhof, trapezoidal, and the uniform distribution.(53) Discrepancies between the vertical pressure measurements and the various theoretical pressure distributions were attributed to the lack of knowledge of the influences of the wall facing element and the frictional stresses that may have developed along the interface between the retained soil and the reinforced soil mass.

Christopher et al. instrumented a 12.6-m high geotextile reinforced wall in Washington designed to provide a preload fill in an area of limited right-of-way, supporting a surcharge fill of more than 5 m in height.(54) The wall was instrumented using:

- 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 geotextile and provide redundancy to the strain gages.
- Inductance coil strain gages placed between reinforcing layers to evaluate lateral strains in the reinforced soil mass.
- Vertical earth pressure cells installed behind the reinforced zone to measure lateral pressures at the back of the reinforced section.
- Inclinometers installed at the face of the wall, in the reinforced section, and behind the reinforced section to measure horizontal movement of the wall.
- Monitoring of vertical movements of the wall by conventional optical surveys and the use of liquid settlement sensing devices installed at the base of the wall.
- Thermistors installed on the reinforcement for measuring internal temperatures of the soil and reinforcement layers, coupled with a weather station.

The instrumentation program was considered to be successful in that most of the instruments survived construction and appeared to provide reasonable results. Several lessons learned applicable to development of an instrumentation program for an MSE wall were as follows:

- The instrumentation should be sensitive over a wide range of strains (i.e., large during construction, and very small following construction).
- The gages and their respective attachment methods must be compatible with the type of reinforcement material.
- The instrumentation program should provide sufficient redundancy to explain anomalous data.
- A sufficient number of instruments spaced preferentially to identify areas of high stress should be provided.
- Measurement of both local and global strains is desirable.
- Calibration of samples of gaged reinforcement is recommended.
- Strain gages should be placed on both top and bottom of the reinforcements to identify bending stresses, etc.
- Temperature effects should be evaluated.
- Continuous monitoring during construction is desirable.

Thamm et al. conducted full-scale testing on a 3.2-m high Websol-wall reinforced with 2.7-m-long geotextile strips which was loaded to failure.(55) Their program employed the following instrumentation:

- Hydraulic pressure cells to measure horizontal earth pressures behind the wall facing.
- Strain gages to measure forces in the geotextile strips.
- Inclinometer casing to determine the horizontal deformations of the wall facing.
- Displacement transducers outside of the wall to measure horizontal deformation of the facing panels and displacement transducers to measure the vertical settlement of the loading concrete slab on the surface.
- One pressure cell for determining the total vertical load placed on the surface of the wall.
- Hydraulic pressure cells for measuring the pressures at the base of the loading concrete slab.

The load was applied to a concrete slab placed in the middle of the wall. Upon application of the first load, the slab settled approximately 25 mm and exhibited visible cracks, coupled with approximately 25 mm movement of the wall facing. The concrete slab reached steady state settlement at a load of 610 kN without taking additional load. Results of the instrumentation program indicated that arching occurred behind the wall facing. This was attributed to the construction procedure using strutted panels in combination with less densification along the first 1.0 m behind the facing. It was found that wedge failure mechanisms may be used for design of structures subjected to high surface loads.

A.6 PERTINENT LITERATURE REVIEW FINDINGS

The literature review conducted to assist in development of this report provided results relevant to the SMSE wall design guidelines:

- 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 for traditional MSE wall construction.

- MSE reinforcement lengths considerably less than $0.7H$ have been successfully employed where the earth pressures are considerably less than active earth pressures ($K<K_a$), such as in the case of MSE walls constructed in front of rock outcrops.[5]

- For narrow or confined walls, the vertical overburden stress is likely less than the unit weight of the overburden multiplied by the wall height ($\sigma_v<\gamma H$) due to arching effects, and these effects require consideration for design of stepped walls.[6]

Results of the literature review determined that the best way to evaluate the use of short MSE reinforcements was through centrifuge modeling. The centrifuge modeling program is presented in appendix B.