CHAPTER 4 – WALLS AND SLOPES

MSE WALLS

MSE walls have been used in public and private projects for at least three decades. Lateral stability and tensile capacity are added to compacted backfill soils by inclusions made of metallic or polymeric strips, grids, and sheets, as shown in Figure 7. MSE walls are more flexible than gravity walls, and they are often more cost effective if adequate space behind the wall is available for development of tensile reinforcement forces.

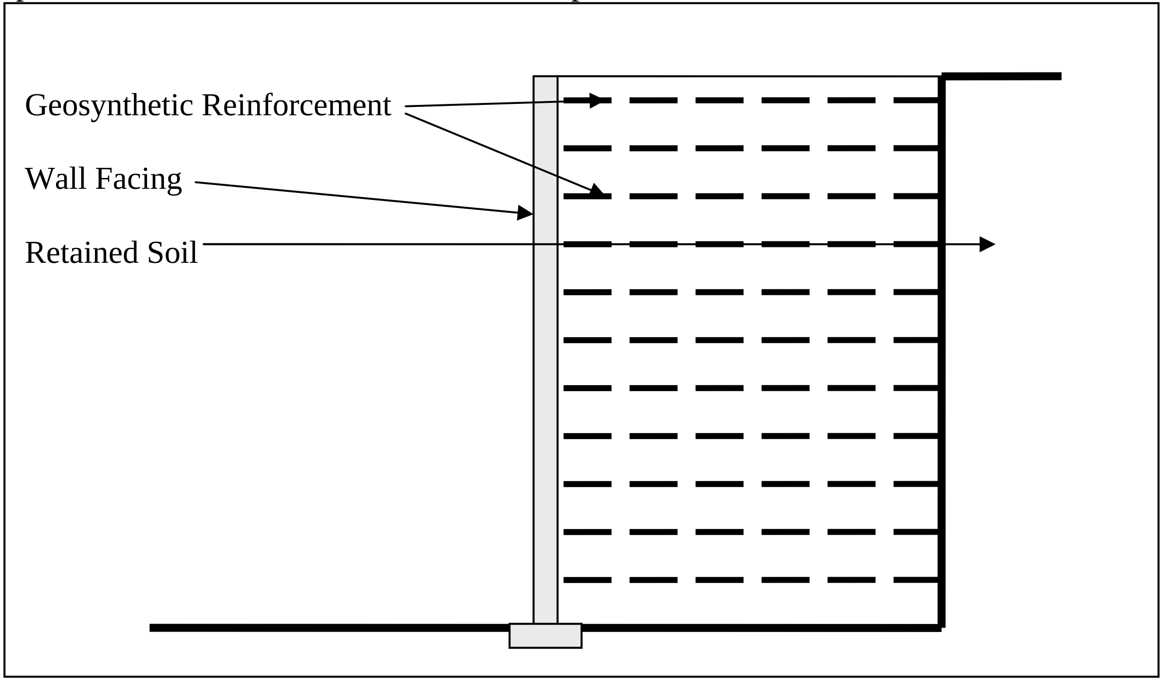

Figure 7. Diagram. Conceptual geometry for MSE wall (after Elias et al., 2001)

Summary of National Guidelines

Elias et al. (2001) summarized the FHWA’s design methodology, considering three main analysis types for internal and external stability and an approach to estimate deformations. The methods outlined allow the user to determine length, spacing and required strength of the geosynthetic reinforcement, and assumes linear and bilinear failure surfaces to determine the required reinforcement tensile strength. The FHWA has sponsored development of specific software, MSEW, (ADAMA Engineering, Inc. 2006) that facilitates design. The FHWA design methodology is consistent with AASHTO (2002).

Seven of 11 survey respondents reported involvement in both unreinforced retaining walls and MSE walls. For unreinforced retaining walls, five of the seven respondents said they had considered or used geosynthetics, likely in drainage, filtration or separation applications. For MSE walls, six of the seven respondents noted geosynthetics were used.

Level of Maturity

Mature. The design and construction of MSE walls has become relatively common around the world. The national design procedures are quite robust, and commercial, FHWA-sponsored software is readily available.

Recent Advances

Design

Christopher et al. (2005) summarized MSE wall design and construction practice in the United States, reviewing the three main methods of analysis used in design: earth pressure, limit equilibrium and continuum mechanics. Earth pressure techniques are currently used in the FHWA design methods to calculate reinforcement tensile forces, while limit equilibrium methods address global stability. Christopher et al. (2005) note that the move to LRFD methods may push U.S. design practice toward more rigorous limit equilibrium methods that require more than moment equilibrium, and may also lead to acceptance of the K-stiffness method proposed by Bathurst et al. (2003).

Bathurst et al. (2003) concluded from a study of 20 geosynthetic MSE wall case histories reported in Allen et al. (2002) that AASHTO design methods result in between 1.5 and 4 times more geosynthetic reinforcement than needed. To reduce this conservatism, Bathurst et al. (2003) considered both failure of the geosynthetic reinforcement by rupture and by failure in the backfill soil, which led to the so-called K-stiffness method, an empirically-based design method that was calibrated using measured reinforcement strains from full scale walls. The method calculates the maximum working tensile load per length of reinforcement based on the shear strength and unit weight of the backfill soil, the area within the wall contributing to the force, and a series of empirical parameters calculated using methods developed by Bathurst et al. (2003).

Allen (2006) presented some results of a monitoring and construction project of an instrumented MSE wall designed using the K-stiffness method. The predicted strains in the reinforcement and resulting horizontal deformations of the wall were conservatively predicted by the K-stiffness method. Allen estimated that use of the K-stiffness method for this wall saved $62,000 in additional geogrid cost compared to an AASHTO design.

Backfill Material

Considering other advances, Christopher et al. (2005) also note the disconnect between public and private practice regarding backfill material. Most designs for public works restrict fines content in the backfill to less than 15%, while private MSE wall projects have seen fines content of 35% or higher. An ongoing NCHRP study, No. 24-22, is scheduled to be completed in 2007 and is investigating the applicability of current design methods to soils containing a higher fine content. This latter point is crucial, since most existing design methodologies, including the K-stiffness method described above, were calibrated using soils with low fines content.

Some geosynthetics manufacturers are also developing products that provide both reinforcement and drainage. Jones (2005) summarizes work in Europe to integrate reinforcement and drainage functions into a single geosynthetic product. Domestically, a similar product was installed at the Salmon/Lost Trail project site in Idaho (Barrows and Lofgren, 1993).

Multi-Tiered and Other Walls

A few researchers have considered design methods for multi-tiered MSE walls. The FHWA recommendations in Elias et al. (2001) include analysis methods for up to two tiers. Wright (2005) proposes a method of preliminary design for multiple tiers that considers the global stability of the entire wall system. Oversimplifying, Wright's process involves constructing a series of MSE walls on top of one another, rather than two independent wall systems as discussed in Elias et al. (2001). Wright (2005)'s observations resulted from analyses and construction methods in use by the Texas DOT.

Leshchinsky and Han (2004) performed a series of numerical studies, looking at whether existing software could adequately predict a factor of safety for multi-tiered walls. They used the limit equilibrium software program ReSSA (Adama Engineering, Inc. 2006) and compared it to the continuum mechanics-based numerical program FLAC (Itasca Consulting Group, 2005). They performed a parametric study considering a wide range of parameters, including water level, reinforcement length, quality of backfill and others, comparing calculated factors of safety and critical failure surfaces from both methods. They concluded the more user-friendly limit equilibrium methods provided similar results to the FLAC results in most cases.

MSE walls have also been combined with soil nail walls to widen and improve a roadway as well as control an area of landslides in Wyoming. Turner and Jensen (2005) describe the construction and monitoring efforts of a slide mitigation and roadway improvement plan that included stabilizing the existing roadway with tiered soil nail walls. The soil nail walls were instrumented to determine the loads carried during construction of the MSE wall, which was built to widen the road's shoulder. The Turner and Jensen (2005)'s main focus was on the performance of the upper soil nail wall, which had a temporary facing that would ultimately be covered by the reinforced earth.

FLHD sponsored a study by Morrison et al. (2006) to develop a design procedure for shored mechanically stabilized earth (SMSE) wall systems. The system considered in this study incorporates contributions from both a soil nail wall for shoring a cut slope and an MSE wall and is shown conceptually in Figure 8. The shoring system in these cases should be designed as a permanent structure, such that lateral forces applied to the MSE wall system are reduced. The study looked at centrifuge and numerical models, as well as an instrumented field test to develop the recommendations. The report suggested a design procedure for the MSE wall component, with design and construction considerations for the shoring system also included.

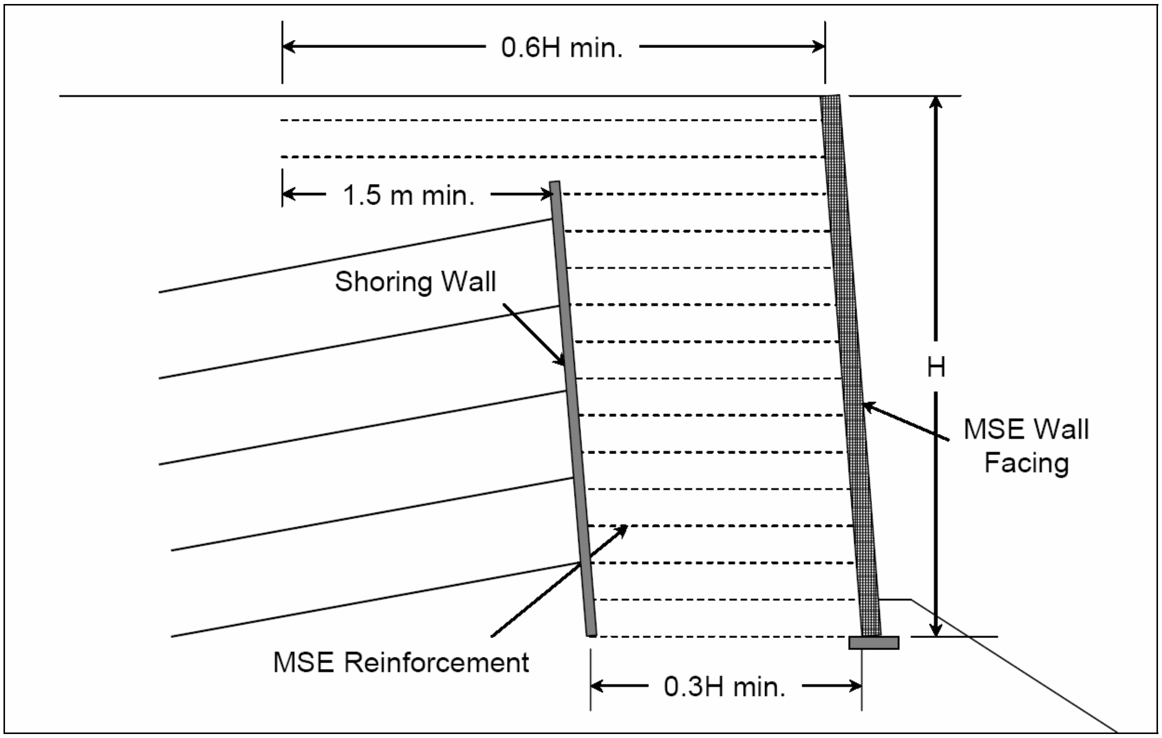

Figure 8. Diagram. Conceptual geometry for SMSE wall (Morrison et al. 2006).

FHWA Durability Studies

Creep deformations have also received attention in the literature. Bueno et al. (2005) review the effects of confinement on the amount of creep experienced by non-woven geotextiles, as well as providing plots of creep vs. log time. Crouse and Wu (2003) also provide a survey of seven monitored MSE wall sites. They observed that the rate of creep in these walls tended to decrease with time, and that deformations due to creep in a wall should therefore slow or diminish with the decreasing creep rate. Allen and Bathurst (2002) make similar observations in their work, also noting that stress relaxation will tend to increase with time.

Gaps in Our Knowledge

Further development of the K-stiffness method and some work towards its validation is already underway in a National Cooperative Highway Research Program (NCHRP) study scheduled to be completed in 2007 (TRB, 2005). This study is focused on application of the method to lower quality backfills (silts and silty sands), as well as building field scale walls for more verification studies. These objectives are necessary for implementation into the AASHTO LRFD Bridge design specifications.

Because the current load and resistance factors for AASHTO LRFD Bridge design specifications (AASHTO 2006) are calibrated to match the factors of safety used in the previous ASD specifications (AASHTO 2002), there are significant gaps in the knowledge of resistance factors for geosynthetic and steel reinforcement. These resistance factor values can only be refined through a statistically significant number of carefully observed case studies, comparing calculated loads to actual measured loads. The vertical earth pressure load factor for MSE walls was developed assuming no inclusions were present. This value, too, should be refined specifically for MSE walls.

Deformation analysis of MSE walls is still quite difficult to perform, and is often assumed to be adequate if specified factors of safety are met (Elias et al., 2001). Vertical deformations are currently based on foundation or embankment settlement methods. An improved method to estimate deformations (either numerically or empirically) would be useful.

The AASHTO LRFD design specifications (AASHTO 2006) note one deficiency in MSE wall design: erosion control. Walls designed near areas where high stream velocities or high piping or seepage forces could occur may be susceptible to damage. In these cases, the soils behind the wall can migrate out into the stream, reducing the soil available to hold up the wall and possibly causing large deformations or collapse. Use of MSE walls in this environment is not recommended.

Currently, design of more complex, multi-tiered wall systems has been largely numerical. Very few published studies have looked at the applicability and safety margins involved in the numerical and theoretical studies proposed in the previous section. As walls get taller and larger, such design methodologies may become more necessary.

SLOPES

Reinforced soil slopes (RSS) are most often specified when highway construction requires a fill slope to be steeper than 1V:2H. In these cases, the new slope is constructed with lifts of compacted backfill and geosynthetic reinforcement. In many ways, RSS are similar to MSE walls, although traditionally MSE walls are defined as having face angles of 0 to 20 degrees from the vertical; slopes tend to have an angle greater than 20 degrees (typical slope angles 45-60 degrees). A conceptual drawing of a reinforced slope is shown in Figure 9.

Short Review of National Guidelines

Elias et al. (2001) discussed design and construction considerations for steepened, reinforced soil slopes. The design method for RSS involves calculating a minimum factor of safety for the slope, with and without reinforcement, for a series of possible failure surfaces. Once reinforcement tensile strength, layer spacing, external and internal stability have been calculated, the engineer must also consider the effects of water infiltration and hydrostatic forces from groundwater, the interaction between the *in situ* and backfill soil, and stabilization of the outer face with either vegetation or something stiffer.

The FHWA has sponsored development of specific software, *ReSSA*, (ADAMA Engineering, Inc. 2006) following FHWA guidelines (Elias et al., 2001) that facilitates design. Other reinforced slope stability programs are commercially available. However, the assumptions used within these other programs may vary from those recommended by FHWA and/or used in the ReSSA program. The use of the ReSSA program is recommended to maintain a consistency in design and equitable bidding environment.

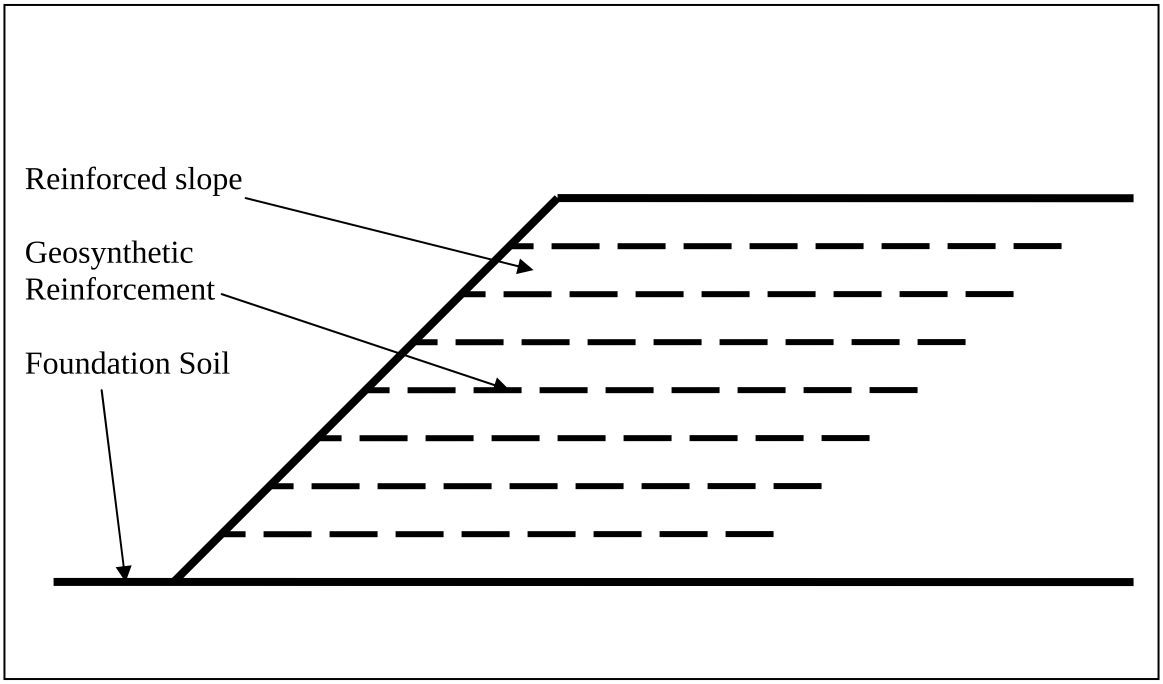

Figure 9. Schematic. Conceptual Reinforced Soil Slope (after Elias et al., 2001 and Koerner, 1998)

One decision the designer must make is the angle at which the reinforcement will deform at the failure surface. The angle of the reinforcement at the failure surface may vary from horizontal to tangent to the failure surface. The most conservative solution occurs when the reinforcement is assumed to be horizontal. Recommendations for selecting an angle to use in the design are not explicitly available.

Level of Maturity

Mature. In many ways, the distinction between constructed slopes and walls is largely a matter of face steepness. That said, reinforced soil slopes and design methods have been in use for many years. However, the maturity of face treatment (a critical element in performance/maintenance) is more localized and varies.

Recent Advances

Recent advances in reinforced soil slopes can be divided into two categories. First, are constructed or steepened slopes, which are the most common type of reinforced slopes. Second, are stabilized natural slopes, where minimal change is made to the face of the slope, but other actions are taken to keep the slope from deteriorating.

Steepened or Constructed Slopes

Christopher et al. (2005) notes the increase in continuum mechanics type analyses for slopes, and the infiltration of these methods into practice. Finite element and finite difference analyses are not limited in the shapes of failure surfaces they can analyze; the plane of lowest shear strength develops "naturally" under a particular loading condition. The problem with these types of analysis is the extent of soil properties required to create the model—while these values can be obtained, they typically are not regularly measured in current practice.

Jones (2005) reports on usage of different design methodologies in Europe. Instead of a method looking at equilibrium of vertical slices, the method presented by Shahgholi et al. (2001) considers horizontal slices. This method, however, is still under development.

Seismic design and performance of reinforced soil slopes has received some attention over the past decade (Ling et al. (1996), Ling et al. (1997), Ausilio et al. (2000), Lo Grasso et al. (2005).). Some methods are highly mathematical, while others are empirical. Nova-Roessig and Sitar (2006) performed centrifuge studies to investigate the seismic response of reinforced soil slopes. They observed that as the intensity of the simulated seismic event is increased, or as the density of the backfill is decreased, or as the stiffness of the reinforcement is decreased, deformations of the slope tended to increase.

Recent field performance and construction studies are described in Fannin (2001a) and Mendoca et al. (2003). In the former case, strains in the reinforcement and temperature in the backfill soils were monitored for three years, and a nonlinear change in force with time was observed. In the latter case, vertical and horizontal deformations, as well as reinforcement strain and earth pressure were measured at a number of points on the wall. Mendoca et al. (2003) observed that horizontal displacements stabilized rather quickly, and that the location along the length of an individual reinforcing layer and the magnitude of maximum strain in the reinforcement changed with time.

Zhang et al. (2003) performed a series of field tests on highway embankment slopes in Louisiana that exhibited signs of failure due to infiltration of water into tension cracks and subsequent saturation of the embankment soils. The slopes were constructed from high plasticity clays, and were rehabilitated using nonwoven geotextiles. They concluded that the nonwoven geotextile used in the study effectively repaired the failing slopes. The repairs were made by excavating a stepped surface for repair, then building the slope back up in lifts of approximately 250 to 300 mm (10 to 12 inches) in height. Based on this study, a very simple slope repair method (presumably using nonwoven geotextiles of similar properties) was suggested.

Finally, FHWA is reportedly developing an updated Slope Maintenance & Slide Restoration Workshop that will incorporate current geosynthetic stabilization techniques. This work is scheduled to be completed in 2007.

Stabilizing Existing Slopes

Anchored geosynthetic slopes are described as a stabilization method for existing saturated sand slopes by Ghiassian et al. (1997). In this case, an existing slope prone to erosion by wind or water is held into place by a geosynthetic that is tensioned by attachment to driven anchors. Depending on the type of geosynthetic chosen, there may be spaces for vegetation to grow, further reducing erosion potential. Mulch mats are described for slope stabilization by Ahn et al. (2002). These multilayered systems consist of a sandwich of seed and fertilizers between geotextiles and a layer of netting. The system reduces erosion and run-off and promotes plant growth over an exposed slope.

Vegetation plays a significant roll in the stability of the face of RSS systems. However, for very steep slopes, greater than 50 degrees; for clean sands and rounded gravel fills; and for silts and sandy silts, other facing systems may be required to provide stability at the face of the slope and protection from erosion. Some of the facing systems that may be considered when secondary reinforcement and vegetation alone are not sufficient are: gabions; geocells; geogrid wrapped face; soil-cement, bioreinforcement; wire baskets; stone and shotcrete. Table 8 (Collin, 1996) provides guidelines for selecting the facing system for various slope angles with different soil types. This table may be used during the preliminary design phase of an RSS system.

Gaps in Our Knowledge

National guidelines do not explicitly cover stabilization of natural slopes, or improvement of rock slopes. In these cases, where future landslides are likely, geosynthetic usage could still have some opportunity for growth. Geosynthetics in tandem with anchor bolts or rock bolts should continue to be considered.

Limit equilibrium methods are well established, although as Christopher et al. (2005) note, the movement toward LRFD may lead to greater usage of methods that satisfy all limit equilibria, not just moment equilibrium. Design schemes based on the results of rigorous finite element or finite difference methods are likely to also be proposed. In these cases, proven models for geosynthetic reinforcement materials and their interaction with the surrounding soils will be required.

DEEP PATCHES FOR SOFT SHOULDERS

This application was developed in the early 1990's as a repair for USFS roads that had shown signs of cracking in the roadway or on the shoulder (see Powell et al., 1999). The cracks were most often noticed on older roads with lower traffic volume, particularly those constructed using a so-called sidecast method. In this method, a natural slope is cut to make the roadway, as shown conceptually in Figure 10. The cut material was then often placed uncompacted on the side of the slope to complete the full shoulder. Over time, water infiltration and other drainage issues led to slope stability problems, as shown by cracks and subsidence in the roadway, and the sidecast section sliding down the original slope.

Table 8. RSS Slope Facing Options (Collin, 1996).

Slope Face Angle and Soil Type	Type of Facing			
	Face not wrapped with geosynthetic		Face wrapped with geosynthetic	
	Vegetated Face	Hard Facing	Vegetated Face	Hard Facing
>50° All Soil Types	Not Recommended	Gabions	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Clean Sands Rounded Gravel	Not Recommended	Gabions Soil-Cement	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Silts Sandy Silts	Bioreinforcement	Gabions Soil-Cement Stone veneer	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Silty Sands Clayey Sands	Temporary or Permanent Erosion Blanket w/ seed or sod	Hard Facing not needed	Geosynthetic wrap not needed	Geosynthetic wrap not needed
25° to 35° All Soil Types	Temporary or Permanent Erosion Blanket w/ seed or sod	Hard Facing not needed	Geosynthetic wrap not needed	Geosynthetic wrap not needed

As a fix, a shallow excavation of a few feet deep is made in the roadway, and replaced by a compacted fill reinforced with one or more layers of geogrid, also shown in Figure 10. The geogrid must be embedded into the area within the natural slope to provide tensile resistance against the slopes movement. Often, a more robust drainage system and a waterproofing geosynthetic in the overlay layer are also added to prevent further water infiltration and slope stability issues (Musser and Denning, 2005). As of 2005, this application has been used in about 100 areas where roadways are failing, predominantly in the west coast states and Colorado.

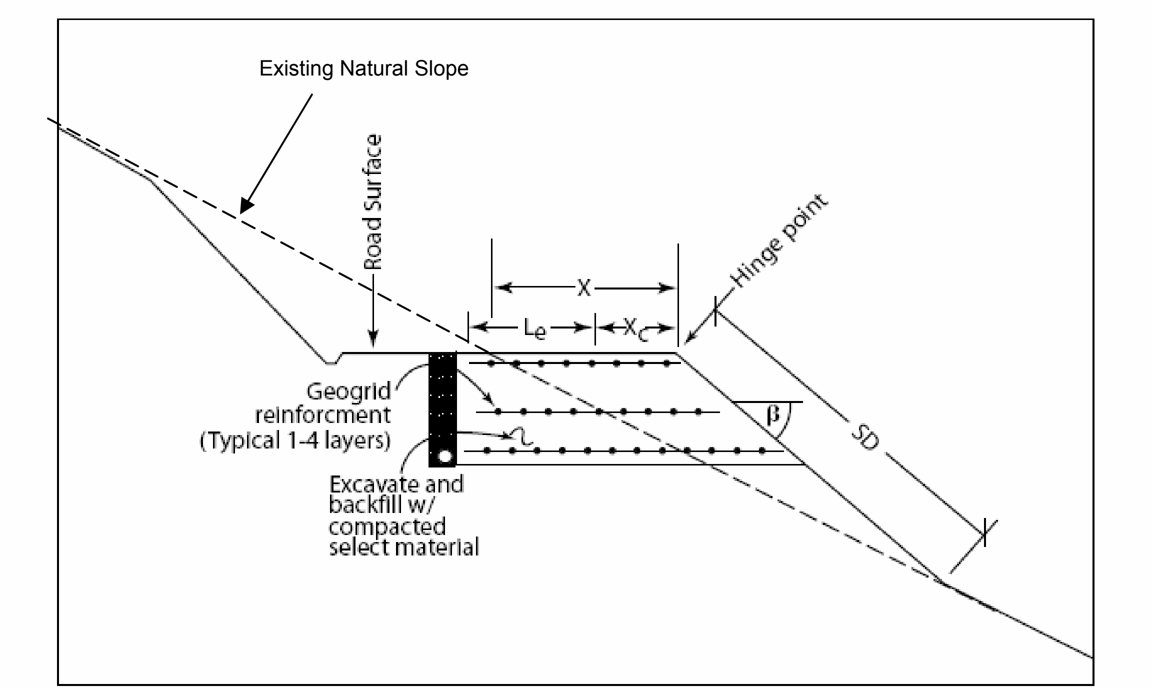

Figure 10. Diagram. Conceptual Geometry of Deep Patch Stabilized Shoulder (modified slightly from Musser and Denning, 2005).

Summary of National Guidelines

There is some documentation from the USFS governing the design of deep patches. The USFS has two design procedures available. The first was described in the FLHD's *Retaining Wall Design Guide* (Mohney, 1994). This method included a 0.9 m (3 ft) deep excavation stabilized with a single layer of geogrid. The geogrid's required strength was not specified, and the required embedment length (L_e in Figure 10) was set equal to the distance from the shoulder edge to the crack furthest from the edge (X_c in Figure 10).

Mohney's 1994 procedure was recently updated by Musser and Denning (2005) based apparently on a series of slope stability analyses. The results were a design method that included a partially solved slope stability problem that could be finished using a series of on-site soil parameters and problem geometry observations in tandem with a series of charts. The results of the analysis determine the required depth of the excavation and the allowable tension in the geogrid for a 1.5 m (5 ft) geogrid embedment length. Once the allowable tension is determined, the total number, depth, and spacing of geogrid layers are calculated. Musser and Denning (2005) also provide construction guidelines.

Based solely on Musser and Denning's guide, it is unclear how much verification using field observations was performed. That said, the method does appear to be a technical improvement over Mahoney's 1994 procedure, if only because it is more flexible concerning depth and geogrid selection.

Six of eleven survey respondents said they were both involved in a deep patch project and used geosynthetics. This would appear to indicate that there has been some penetration of the Mohney's methods described above.

Level of Maturity

Undeveloped to Developing. While a design method is available, there is still some need to standardize and validate the models for deeper patches. This application still requires monitoring of the long term efficacy of the repair and standardizing the design method for more complicated situations.

Recent Advances

Wu and Helwany (2001) created a "deep-patch test apparatus" to test the effects of the reinforcement used in the deep patch technique. This device allowed more or less full scale, plane strain tests. The apparatus allowed reinforced depth of over 2.1 m (7 ft) and a slope of approximately 1.2 to 1. The slope failure was modeled by creating a movable section that would drop out, mimicking movement of the soil below a portion of the patch due to a slide.

Wu and Helwany (2001) monitored the strain in the five embedded geotextile layers (geogrids are more typically used in practice). The benefits of the reinforced section were clear: in the reinforced section, minor localized cracking near the slope face was observed, while the unreinforced section showed near vertical cracks in the modeled shoulder. Other than Wu and Helwany's (2001) work, most of the advances in deep patch design and implementation appear to be occurring in the field but remain undocumented.

Gaps in Our Knowledge

Musser and Denning's (2005) design methodology does not include observed field comparison cases. Similarly, it does not include recommendations for steps to take or analysis procedures to use for more complicated situations. Thus, a wider scale search of past and present deep patch projects, with some possible instrumentation or long term monitoring are advisable. Reportedly, one project is already underway that looks at the history of deep patch repairs and monitors 10-15 existing and new deep patch sites for two years. These observations focus on rates of movement of the failing slope and propagation of cracks (FLHD CTIP, 2006).

SUMMARY

The use of geosynthetics in slopes and wall reinforcement has received considerable attention over the last few decades. The design methods are quite mature, and a number of successful case histories are available. MSE walls and reinforced soil slopes have become standard construction tools throughout the country, in both private and public projects. The deep patch method is also gaining acceptance, although the design methods in practice could use additional refinement and verification.