Review of Stability Berm Alternatives for Environmentally Sensitive Areas

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Iowa State University

Final Report • June 2005

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16. Abstract

Stability berms are commonly constructed where roadway embankments cross soft or unstable ground conditions. Under certain circumstances, the construction of stability berms cause unfavorable environmental impacts, either directly or indirectly, through their effect on wetlands, endangered species habitat, stream channelization, longer culvert lengths, larger right-of-way purchases, and construction access limits. Due to an ever more restrictive regulatory environment, these impacts are problematic. The result is the loss of valuable natural resources to the public, lengthy permitting review processes for the department of transportation and permitting agencies, and the additional expenditures of time and money for all parties.

The purpose of this project was to review existing stability berm alternatives for potential use in environmentally sensitive areas. The project also evaluates how stabilization technologies are made feasible, desirable, and cost-effective for transportation projects and determines which alternatives afford practical solutions for avoiding and minimizing impacts to environmentally sensitive areas.

An online survey of engineers at state departments of transportation was also conducted to assess the frequency and cost effectiveness of the various stabilization technologies. Geotechnical engineers that responded to the survey overwhelmingly use geosynthetic reinforcement as a suitable and cost-effective solution for stabilizing embankments and cut slopes. Alternatively, chemical stabilization and installation of lime/cement columns is rarely a remediation measure employed by state departments of transportation.

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REVIEW OF STABILITY BERM ALTERNATIVES FOR ENVIRONMENTALLY SENSITIVE AREAS

Iowa DOT Project CSMR(5)--90-00
CTRE Project 05-203

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The finding, opinion, recommendations, and conclusions expressed in this report are those of the authors and do not necessarily reflect the views of the sponsor and administrations.

EXECUTIVE SUMMARY

Stability berms are commonly constructed where roadway embankments cross soft or unstable ground conditions. Under certain circumstances, the construction of stability berms cause unfavorable environmental impacts, either directly or indirectly, through their effect on wetlands, endangered species habitat, stream channelization, longer culvert lengths, larger right-of-way purchases, and construction access limits. Due to an ever more restrictive regulatory environment, these impacts are problematic. The result is the loss of valuable natural resources to the public, lengthy permitting review processes for the department of transportation and permitting agencies, and the additional expenditures of time and money for all parties. To more adequately address avoidance and minimization aspects of environmental permitting, a review of alternatives to stability berm construction was conducted.

Alternative technologies documented in this report for possible use in place of stability berms include the following: (1) lightweight fill, (2) geosynthetic reinforcement, (3) stone columns, (4) Geopier rammed aggregate piers, (5) lime/cement columns, (6) soil nailing, (7) soil nail launching, (8) pile stabilization, and (9) preloading and wick drains. Each remedial method is discussed considering the stabilization mechanism, technology limitations, and approximate costs.

An online survey of engineers at state departments of transportation was also conducted to assess the frequency and cost effectiveness of the various stabilization technologies. Information provided by the respondents is useful for inferring the relative effectiveness of each remedial measure. Geotechnical engineers that responded to the survey overwhelmingly use geosynthetic reinforcement as a suitable and cost-effective solution for stabilizing embankments and cut slopes. Alternatively, chemical stabilization and installation of lime/cement columns is seldom a remediation measure employed by state departments of transportation.

A simplified flowchart was developed to incorporate the necessary tasks for selecting a stability berm alternative into general planning and preliminary design processes. The procedure begins by identifying the need for slope remediation, based on performance requirements of the engineered slope and environmental impact of conventional earthwork practices. The preliminary design of stabilization alternatives assesses initial costs, the potential for failure, and the cost of a failure. This information can be applied directly to risk management policies of the transportation agency, and the most appropriate remediation alternative can be selected.

INTRODUCTION

Purpose of Investigation

The purpose of this project is to review existing stability berm alternatives for potential use in environmentally sensitive areas. The project also evaluates how stabilization technologies are made feasible, desirable, and cost-effective for transportation projects and determines which alternatives afford practical solutions for avoiding and minimizing impacts to environmentally sensitive areas.

Project Scope

The report reviews geotechnical aspects of embankment stability, summarizing the key concepts of slope stability and stabilization. Conceptual understanding of the presented topics aids the decision-making process of selecting an appropriate alternative to the design and construction of embankment stability berms. The information may otherwise suggest that a stability berm is, in fact, the most cost-effective solution to slope instability for a particular project.

Report Organization

Slope Instability of Highway Embankments provides an introduction to the problem of embankment slope instability. General causes of slope instability are stated to demonstrate the need for embankment stabilization alternatives, and stability berms are briefly discussed considering their purpose and their environmental impacts.

Stabilization Technologies presents alternatives to the construction of stability berms, acknowledging the adverse environmental impacts of some stabilization practices. Stabilizing mechanisms, design parameters, construction difficulties, and available cost issues are documented for each of the technologies.

Survey of Practice documents the state-of-practice for embankment stabilization by state departments of transportation. A summary of responses to an online questionnaire indicates the various design and construction practices used by state departments of transportation and various stability berm alternatives.

Guidance in Stability Berm Alternative Selection offers assistance in interpreting which stabilization technologies may be appropriate for use in eliminating embankment stability berms. Geotechnical considerations for selecting a stability berm alternative are noted, and a proposed process for planning and preliminary design of an engineered embankment slope is suggested.

Final Remarks presents the conclusions of the investigative study and addresses the goals of the literature synthesis.

Literature and References

This report serves as a guide to evaluate the differing embankment stabilization alternatives that may be used in environmentally sensitive areas. Focus is placed on explaining the stabilizing mechanism of each alternative and discussing pertinent geotechnical considerations associated with selecting a stability berm alternative. The report is not a comprehensive document that contains complete design methodologies or case histories. To more completely understand each report topic, however, useful references are provided under separate cover. These references can be consulted for additional information regarding design procedures, construction details, costs, and research results.

SLOPE INSTABILITY OF HIGHWAY EMBANKMENTS

Slope Stability Evaluation

Foundation soils and embankments provide adequate support for roadways and other transportation infrastructure if the additional stress from traffic loads and geostructures does not exceed the shear strength of the embankment soils or underlying strata (Ariema and Butler 1990). Overstressing the embankment or foundation soil may result in rotational, displacement, or translatory failure, as illustrated in Figure 1.

Factors of safety (FS) are used to indicate the adequacy of slope stability and play a vital role in the rational design of engineered slopes (e.g., embankments, cut slopes, landfills). Factors of safety are used in design account for uncertainty and thus guard against ignorance about the reliability of the items that enter into the analysis, such as soil strength parameter values, pore water pressure distributions, and soil stratigraphy (Abramson et al. 2002). As with the design of other geostructures, higher factors of safety are used when limited site investigation generates uncertainty regarding the analysis input parameters. Investment in more thorough site investigation and construction monitoring, however, may be rewarded by acceptable reduction in the desired factor of safety. Typically, minimum factors of safety for new embankment slope design range from 1.3 to 1.5.

Factors of safety against slope instability are defined considering the likely slope failure mode and the strength of slope soils. Factor of safety values are obtained using three general methods (mobilized strength, ratio of forces, or ratio of moments), but are not necessarily identical for Mohr-Coulomb (ϕ-c) soils. The various definitions for factor of safety are provided in Table 1. The complete theoretical development, selection, and use of limit equilibrium methods for evaluating slope stability are beyond the scope of this report. For a more complete introduction to slope stability design and analysis see *Slope Stability and Stabilization Methods* by Abramson et al. (2002).

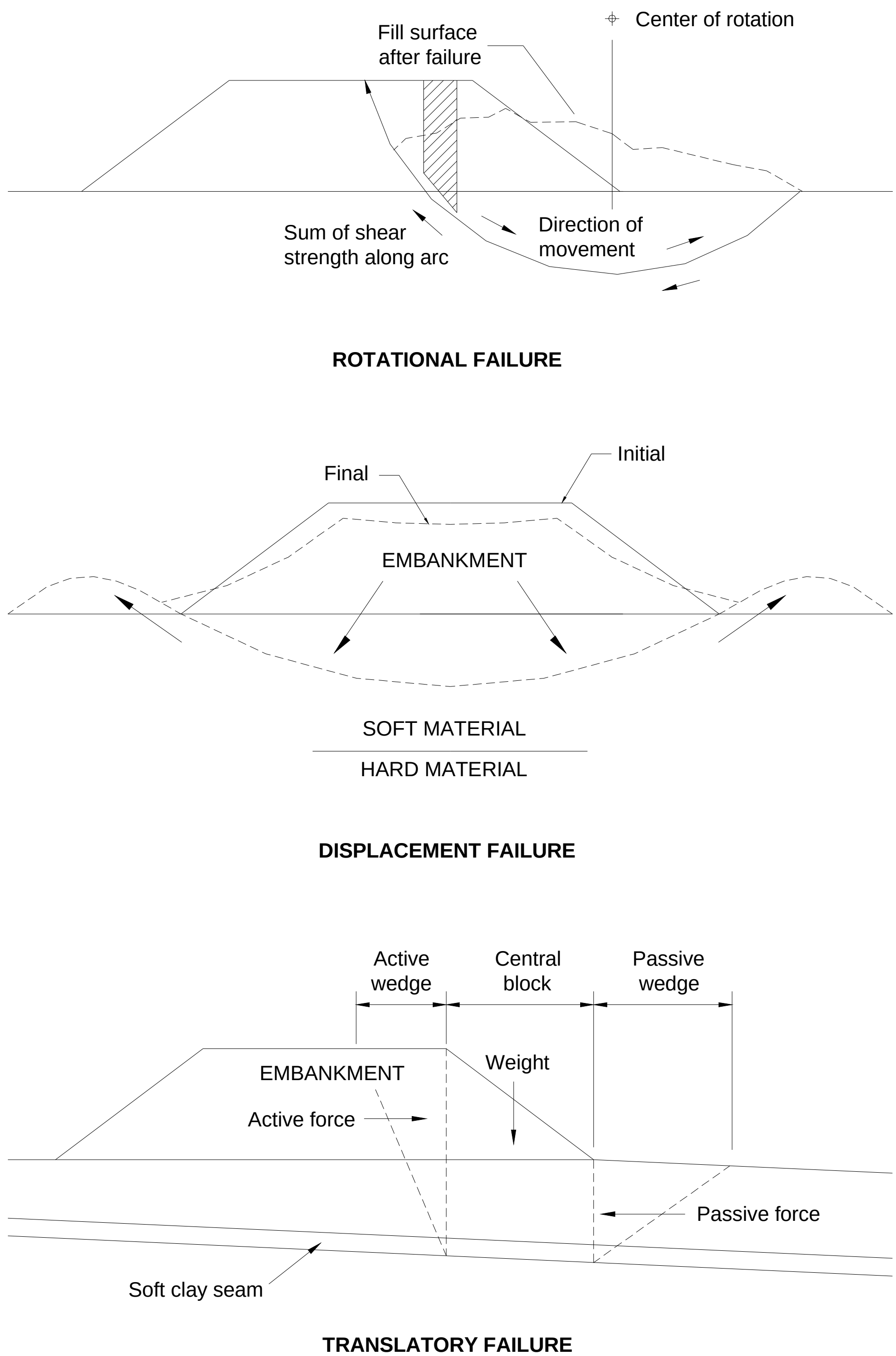


Figure 1. Typical embankment failures (Ariema and Butler 1990)

Table 1. Factor of safety definitions

Name	Definition	Condition
Limit equilibrium or Mobilized strength	$FS = \dfrac{s_u}{\tau_{required}}$	(Total stress)
	$\dfrac{c' + \sigma' \tan \phi'}{\tau_{required}}$	(Effective stress)
Forces	$FS = \dfrac{\text{Sum of resisting forces}}{\text{Sum of mobilized forces}}$	
Moments	$FS = \dfrac{\text{Resisting moment}}{\text{Overturning moment}}$	
	$\dfrac{R \int s_u \, ds}{W x}$	

Parameter definitions:
FS = factor of safety
s_u = undrained shear strength
$\tau_{required}$ = shear stress mobilized for equilibrium
c' = effective cohesion
ϕ' = effective friction angle
R = radius of rotational failure
W x = moment driving slope movement, attributed to soil weight

Causes of Slope Instability

Stable slopes are characterized by a balance between the gravitational forces tending to pull soils downslope and the resisting forces comprised of soil shear strength. The state of temporary equilibrium may be compromised when the slope is subject to destabilizing forces. The factors affecting slope stability may include those that increase the gravitational force (e.g., slope geometry, undercutting, surcharging) or those that reduce soil shear strength (e.g., weathering, pore water pressure, vegetation removal) (Chatwin et al. 1994).

Slope Stability Problems in Iowa

Slope instability poses problems for highway systems in Iowa. Failures occur on both new embankments and cut slopes. The failures occur because identifying factors that affect stability at a particular location, such as soil shear strength parameter values, ground water surface elevations, and negative influences from construction activities, are often difficult to discern and measure. Hazard identification is a cornerstone of landslide hazard mitigation (Spiker and Gori

2003). Once a failure occurs or a potential failure is identified (i.e., low factor of safety), highway agencies need information and knowledge of which methods of remediation will be most effective to stabilize the slope. Ideally, these stability problems can be discovered and addressed before a slope failure occurs.

The application for slope remediation technologies is evidenced by a survey of Iowa county engineers conducted in 2001. The data show that 80 percent of the responding counties have experienced slope stability problems. The percent of Iowa counties having experienced various slope failure conditions (e.g., soil type, location) is provided in Figure 2. From Figure 2, approximately 52 percent of the slope remediation projects involve changes in slope geometry (in effect creating a stability berm). The design and construction of stability berms has historically been a simple and effective option of departments of transportation for preserving transportation infrastructure.

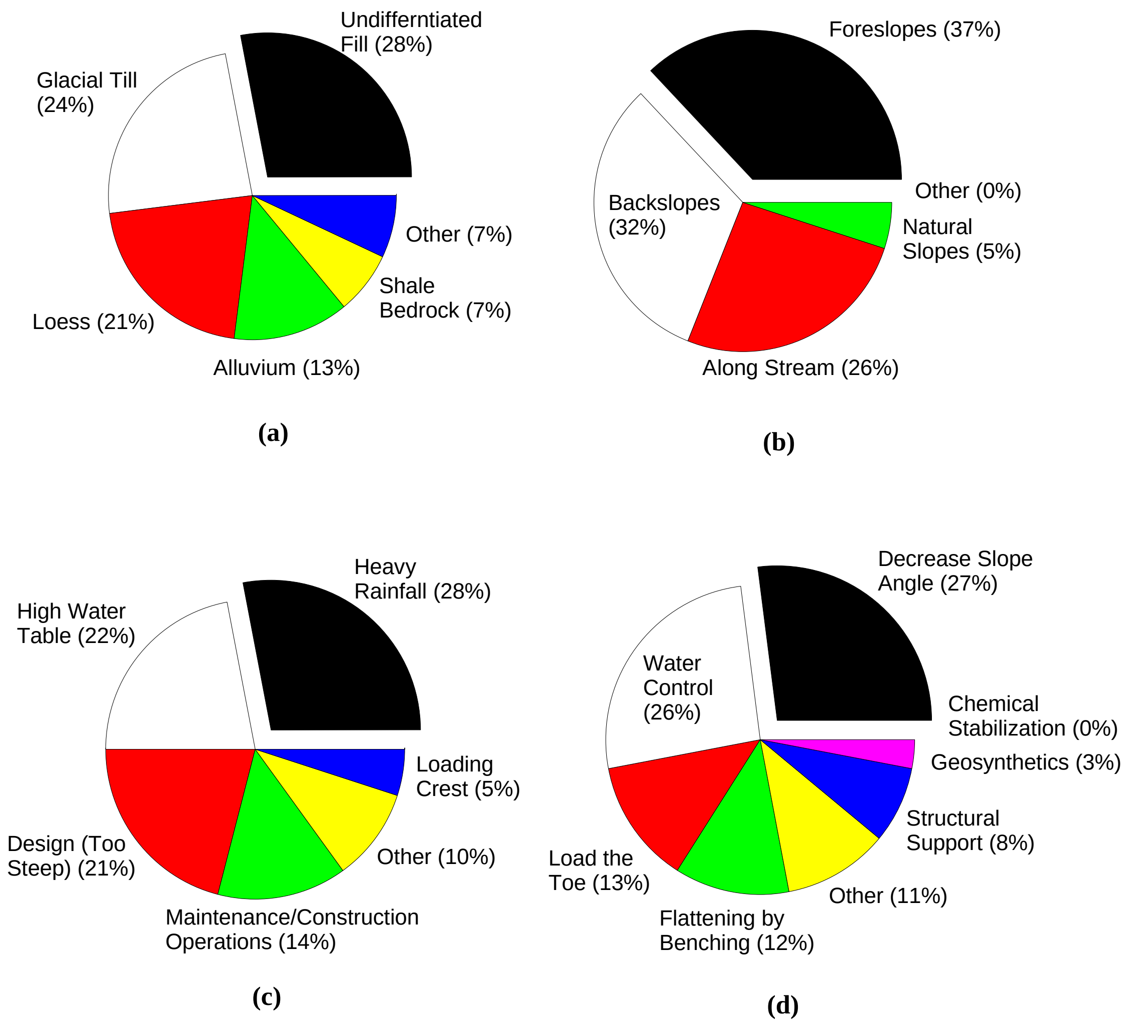


Figure 2. Conditions of Iowa slope failures (after Lohnes et al. 2001): (a) soil type, (b) location, (c) probable cause, and (d) remediation

What Are Stability Berms?

Stability berms (see Figure 3) are constructed of fill materials at the toe of slopes and provide a counterweight to resist deep, rotational failures (FHWA 1988). Berms, which often require considerable fill volumes, may also be used to repair small slides where the slope toe has been steepened by erosion or construction activities. The weight of stability berms increases the force resisting slope movement and reduces the net driving force for the critical failure surface by increasing the length and depth of potential failure surfaces.

Stability berms are designed and analyzed with different slopes and cross-sectional dimensions to ensure that the berm does not increase driving forces and that likely failure surfaces extend beyond the limits of the berm. The berm must also be designed to assure global stability of the berm itself. Stability berms constructed on soft soils may increase the total settlement, especially of the outer edges of the embankment (Holtz 1989). Settlement analyses usually accompany stability analyses for slopes stabilized with berms.

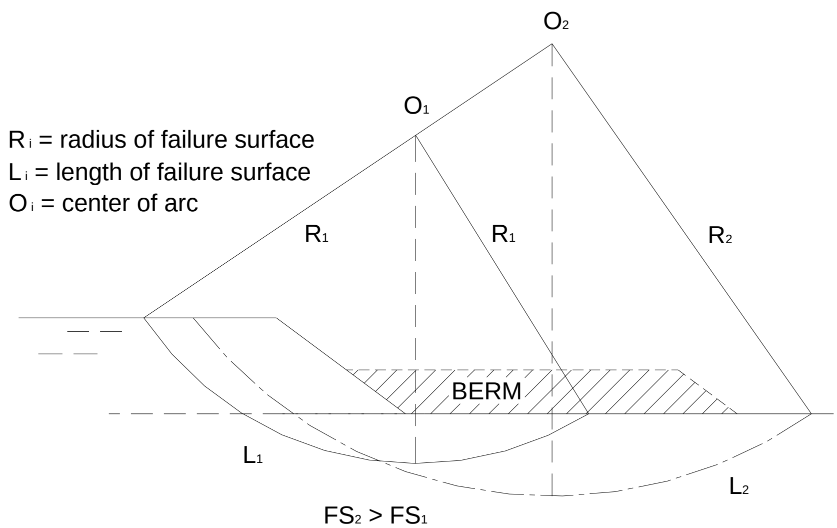


Figure 3. Effect of berm for slope stabilization (from Abramson et al. 2002)

Environmental Impacts of Stability Berms

Stability berms are commonly constructed where roadway embankments cross soft or unstable ground conditions. Under certain circumstances, the construction of stability berms cause unfavorable environmental impacts, either directly or indirectly, through their effect on wetlands, endangered species habitat, stream channelization, longer culvert lengths, larger right-of-way purchases, and construction access limits. Due to an ever more restrictive regulatory environment, these impacts are problematic. The result is the loss of valuable natural resources to the public, lengthy permitting review processes for the department of transportation and permitting agencies, and the additional expenditures of time and money for all parties. To more adequately address avoidance and minimization aspects of environmental permitting, a review of alternatives to stability berm construction was conducted.

Stability Berm Alternatives

Remedial methods for arresting or preventing slope movement must consider the specific causal factors contributing to slope instability. Beyond this fundamental notion, the selection of an appropriate remedial method must also address engineering and economic feasibility, as well as social and environmental acceptability (Popescu 1994).

Engineers charged with the responsibility of planning, designing, and implementing improvements need to understand the applications, technology limitations, and costs associated with the available technologies. The objective of discussing possible solutions to slope instability is to demonstrate the scope of remedial methods. Excavation methods alter slope geometry (e.g., slope flattening and stability berms) for improved stability. As these methods have adverse environmental impact through increased embankment footprint area, they were not discussed as recommended solutions to slope instability in environmentally sensitive areas. Overexcavation (i.e., excavate and replace) is an alternative for increasing the stability of an embankment, as use of geomaterials with superior engineering properties may eliminate slope instability and need for stabilizing technologies. The stabilization technologies discussed in the following chapter as alternatives to stability berms include the following: (1) lightweight fill, (2) geosynthetic reinforcement, (3) stone columns, (4) *Geopier* rammed aggregate piers, (5) lime/cement columns, (6) soil nailing, (7) soil nail launching, (8) pile stabilization, and (9) preloading and wick drains.

STABILIZATION TECHNOLOGIES

Lightweight Fill

Placement of lightweight fill material in embankments can reduce the driving force of the slope, as the compacted densities of lightweight fill materials are significantly less than natural soils. Lighter overburden results in a reduction of the gravitational forces driving slope movement, thereby increasing slope stability. Many lightweight fill materials also have a high internal angle of shearing resistance, further contributing to slope stability (Holtz 1989). Lightweight materials, such as slag, encapsulated sawdust, expanded shale, cinders, shredded rubber tires, and expanded polystyrene foam have been used with success, but mostly at the research level. The unit weights and recommended use of lightweight materials are provided in Table 2. Approximate costs for the materials are provided in Table 3.

Detailed use of lightweight fill materials in embankments, inclusive of material properties, design concepts, cost data, and case histories is found in the following references:

- Federal Highway Administration. 1998. *Ground Improvement Technical Summaries, Vol. I*, FHWA-SA-98-086, Washington, D.C.
- Holtz, R. 1989. *Treatment of Problem Foundations for Highway Embankments*. National Cooperative Highway Research Program Report No. 147, Washington D.C.

Geofoam

Expanded polystyrene (EPS) geofoam has been used for ultra lightweight fill (unit weights from 1 to 6 pcf) since the 1960's (Anon 1986). The material, which may be 100 times lighter than compacted soil, comes in boards that can be placed like interlocking brickwork and thus is stable at very steep angles (Leventhal and Mostyn 1986). Construction with EPS geofoam requires only basic tools, such as a chainsaw to trim blocks to the desired shape. The major components of an EPS-block geofoam embankment are illustrated in Figure 4, and soil compaction adjacent to geofoam fill is shown in Figure 5.

A typical cross section through a trapezoidal EPS embankment with sideslopes of 2H:1V is shown in Figure 6. The results of stability analyses for trapezoidal embankments (and also vertical embankments) of typical cross sections were used to develop design charts for static external slope stability. Design charts, which require input of embankment geometry and undrained shear strength of soil cover, are provided in "Guideline and Recommended Standard for Geofoam Applications in Highway Embankments" NCHRP Report No. 529 by Stark et al. (2004).

EPS geofoam is expensive compared to soil fill, costing up to $\$100/yd^3$ or more, as opposed to approximately $\$3/yd^3$ for earth fill. In many instances, transportation costs alone have made the use of a lightweight material uneconomical, but each case should be examined on its merits. Judicious use of the manufactured material can be justified when specific slope geometry must be achieved (Leventhal and Mostyn 1986).

Table 2. Lightweight embankment fill materials (Holtz 1989)

Material	Unit Weight		Comments
	kN/m^3	lb/ft^3	
Bark (Pine and Fir)	8-10	35-64	Waste material used relatively rarely as it is difficult to compact. The risk of leached water from the bark polluting groundwater can be reduced or eliminated by using material initially stored in water and then allowed to air dry for some months. The compacted/loose volume ratio is on the order of 50 percent. Long-term settlement of bark fill may amount to 10 percent of compacted thickness.
Sawdust (Pine and Fir)	8-10	50-64	Waste material that is normally used below permanent groundwater level but has occasionally been employed for embankments that have had the side slopes sealed by asphalt or geomembrane.
Peat:			Proved particularly useful in Ireland for repairing existing roads by replacing gravel fills with baled peat.
Air dried: milled	3-5	19-32	
Baled horticultural	2	13	
compressed bales	8-10	51-64	
Fuel ash, slag, Cinders, etc.	10-14	64-100	Waste materials such as pulverized fuel ash (PFA) are generally placed at least 0.3 m above maximum flood level. Such materials may have cementing properties producing a significant increase in factor of safety with time. In some cases, the materials absorb water with time, resulting in an increase in density.
Scrap cellular concrete	10	64	Significant volume decrease results when the material is compacted. Excessive compaction reduces the material to a powder.
Low-density cellular concrete	6	38	This is an experimental lightweight fill material manufactured from portland cement, water, and a foaming agent with the trade name Elastizell™. The material is cast in situ.

Table 2. (*continued*)

Material	Unit Weight		Comments
	kN/m^3	**lb/ft^3**	
Expanded clay or Shale (lightweight aggregate)	3-10	20-64	The physical properties of this material, such as density, resistance, and compressibility, are generally very good for use as a lightweight fill, although some variations may be produced by the different manufacturing processes. The material is relatively expensive but can prove economical in comparison with other techniques for constructing high-standard roads. The minimum thickness of road pavement above the expanded clay is generally on the order of 0.6 m.
Expanded polystyrene	0.2-1	1.3-6	This is a superlight material used in Norway, Sweden, the United States, and Canada up to the present, but where its performance has proved very satisfactory and its usage is increasing. In Norway, the material is used in blocks. The thickness of the cover varies between 0.5 and 1 m, depending on traffic-loading conditions. Incorporated with the pavement is a reinforced concrete slab cast directly on the polystyrene to reduce deformation and provide protection against oil, etc. The material is very expensive, but the very low density may make it economical is special circumstances.
Shells (oyster, clam, etc.)	11	70	Commercially mined or dredged shells available mainly on Gulf and Atlantic coasts. Sizes 0.5 to 3 in (12 to 75 mm). When loosely dumped, shells have a low density and high bearing capacity because of interlock.

Table 3. Approximate costs for lightweight fill materials (from Elias et al. 1998)

Material	Approximate Cost $/m^3$
Geofoam (EPS)	35-65
Foamed Concrete	55-85
Wood Fiber	12-20
Shredded Tires	20-30
Expanded Shale and Clay	40-55
Fly ash	15-21
Boiler Slag	3-4
Air Cooled Slag	7-9

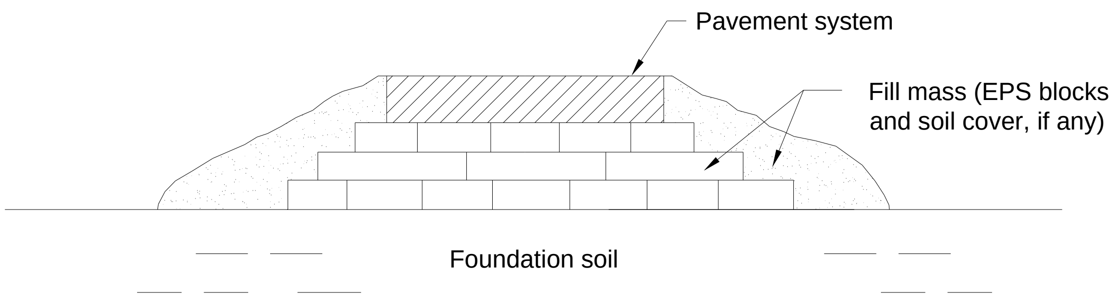


Figure 4. Major components of an EPS embankment (reproduced from Stark et al. 2004)

Figure 5. Soil compaction adjacent to geofoam fill (from Negussey and Stuedlein 2003)

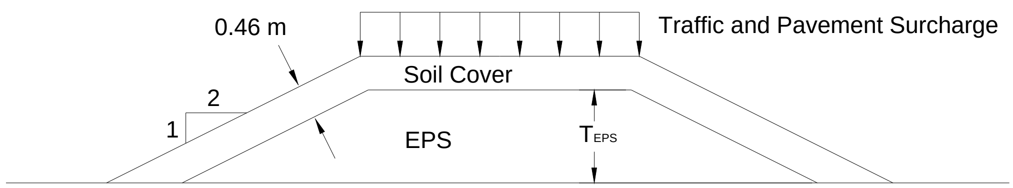


Figure 6. Typical cross section used in static slope stability analyses of embankments (reproduced from Stark et al. 2004)

Shredded Tires

The use of shredded tires in highway applications is a significant method for putting scrap tires into beneficial reuse (Bosscher et al. 1997). Shredded tires can be used as aggregate replacement in construction of non-structural fill, pavement frost barriers, retaining wall backfill, and lightweight embankment fill crossing soft or unstable ground. The lightweight fill application is particularly interesting, because it provides a means of disposing scrap tires and also helps to solve economical and technical problems associated with settlement and instability of highway construction over soft ground (Bosscher et al. 1997).

As a lightweight fill material, shredded tires have material properties which vary from other lightweight fill materials. Tire shredding operations may result in different particle sizes, such that the gradation of shredded tires tends to be random to uniformly graded (Han 1998). Bulk unit weights may range from 2.2 to 3.5 kN/m^3 (14 to 22 pcf), and the angles of internal friction and cohesion are approximately 18 degrees and 28 kPa, respectively (Han 1998). Shredded tires are more compressible than some alternative lightweight fill materials, and the deformation of shredded tires under load following construction should be accounted for in the design.

Vehicle tires today contain metal additives and metal belts and bead wire, as well as petroleum (Han 1998). Application of shredded tires as lightweight fill materials to road construction has resulted in concerns regarding environmental and fire hazards, recognizing that groundwater contamination is the primary concern when the lightweight fill is placed beneath the water table.

In general, the crushing strength of some lightweight fill materials can be relatively low, and care must be taken during construction to avoid damaging the materials, especially if conventional compaction equipment is used (Holtz 1989). Lightweight fill materials may also not be suitable for use as part of the pavement structure. Scrap lightweight concrete, for example, is susceptible to freezing problems. The seasonal climate changes of Iowa require that any lightweight fill application be durable with respect to freeze-thaw and wetting-drying cycles.

Geosynthetic Reinforcement

Geosynthetics are flexible polymeric materials that offer an effective reinforcement method for slope stabilization (Holtz et al. 1997). Using geotextile or geogrid reinforces soils with inadequate in situ strength by adding tensile resistance to the reinforced soil system. Stresses applied to a soil mass cause soil strain. Friction develops at locations where there is relative shear displacement and corresponding shear stress between soil and reinforcement surface (Elias et al. 2001), such that tensile loads are transmitted to the reinforcement. The displacements are restrained in the direction of the reinforcement, causing the reinforced soil mass to behave like a cohesive anisotropic material (Schlosser and Bastick 1991). In the case of protecting a slope from failure along existing or likely failure surfaces, reinforcement is placed to extend beyond the failure surfaces. Tension is more directly mobilized, resulting in deeper failure surfaces which are associated with a higher degree of stability.

Mechanically stabilized earth (MSE) walls and reinforced soil slopes (RSS) have been widely constructed. The following references offer details for the design and construction of the earth stabilization technology:

- Elias, V., Christopher, B. and R. Berg. 2001. *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines*, Federal Highway Administration Report No. FHWA-NHI-00-043.

- Holtz, R., Christopher, B. and R. Berg. 1997. Geosynthetic Engineering, BiTech Publishers Ltd., Richmond.

Mechanically Stabilized Earth (MSE) Walls

MSE walls are structural alternatives for applications where reinforced concrete or gravity type walls have traditionally been used to retain soil (Elias et al. 2001). Applications of MSE walls may include bridge abutments and wing walls, as well as areas where right-of-way is restricted and an embankment or excavation with steep, stable side slopes cannot be constructed.

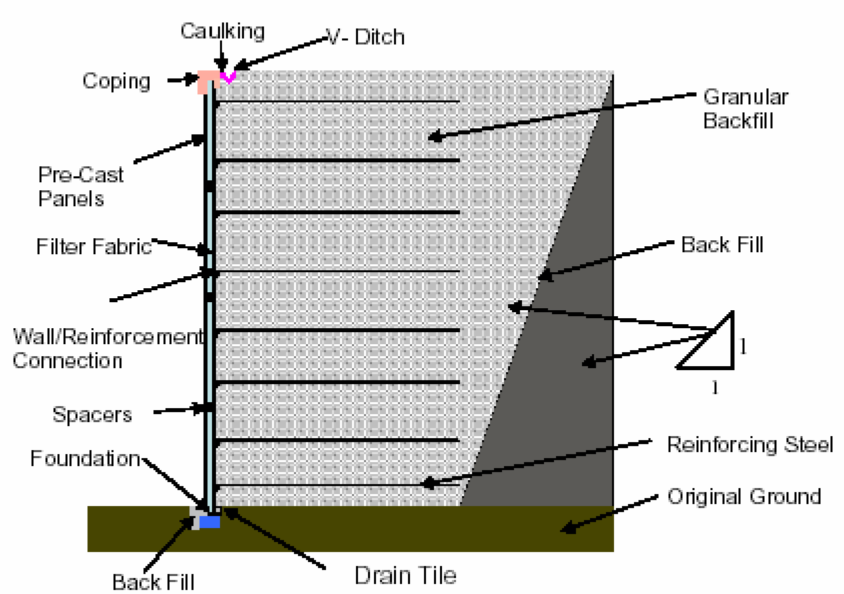
Current design practices consist of determining the geometric and reinforcement requirements to prevent internal and external failure using limit equilibrium methods of analysis (Elias et al. 2001). External stability analyses of MSE walls regard the reinforced soil mass as a composite, homogeneous material, allowing for evaluation of stability according to the conventional failure modes for gravity type wall systems. Internal stability evaluations determine the reinforcement required and deviate from traditional analyses in evaluating the development of internal lateral stress and finding the most critical failure surface (Elias et al. 2001). Internal stability is treated as a response of discrete elements in a soil mass, suggesting that deformations are controlled by reinforcement.

The cost of soil-reinforced structures depends on wall size and type, soil conditions, available backfill materials, and facing specifications. MSE walls with precast concrete facings are usually less expensive than reinforced concrete retaining walls for heights greater than 10 feet and average foundation conditions (Elias et al. 2001). In general, the use of MSE walls results in savings of 25 to 50 percent over conventional reinforced concrete retaining structures, especially when the latter is supported on a deep foundation system. Other cost saving features may include ease and speed of construction, as well as savings in wall materials. A comparison of wall material and erection costs for several retaining wall systems, based on a survey of state and federal transportation agencies, is shown in Figure 8. Typical total costs for MSE walls range from \$200 to \$400 per m^2, generally as a function of height, project size, and select fill costs (Elias et al. 2001).

The components and construction of MSE walls are shown in Figure 7. The cost of constructing an MSE wall depends on the cost of its primary components. Typical relative costs are the following:

- Erection of panels and contractors profit - 20 to 30 percent of total cost
- Reinforcement - 20 to 30 percent of total cost
- Backfill - 30 to 45 percent of total cost
- Face treatment - 25 to 30 percent of total cost

The cost of excavation must be considered, as this cost may be greater for geosynthetic reinforcement than for other systems.



(a)

(b)

Figure 7. Components and construction of MSE walls (from Makarla 2004)

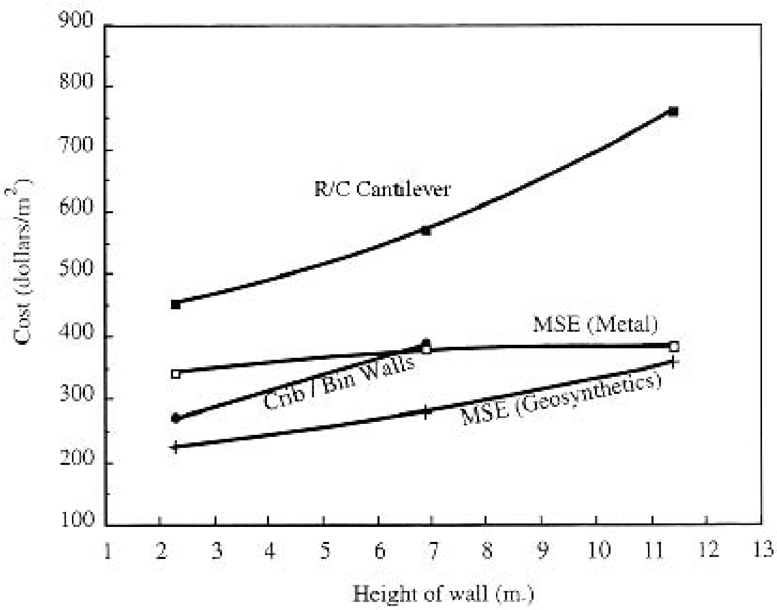


Figure 8. Cost comparison for retaining wall systems (from Elias et al. 2001)

Reinforced Soil Slopes

The reinforcement method and application of reinforced soil slopes can be particularly effective when the cost of fill, limited right-of-way, or adverse environmental impacts of stability berms make steep slopes desirable. Common applications for reinforced soil slopes are illustrated in Figure 9. Construction of a reinforced soil slope in West Virginia is shown in Figure 10.

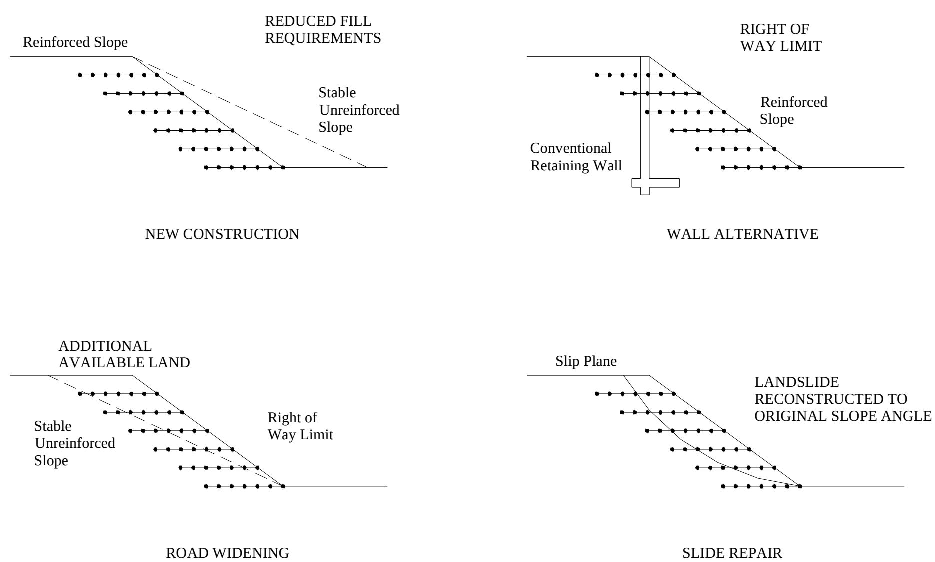


Figure 9. Applications of reinforced slopes (reproduced from Holtz et al. 1997)

The principal purpose of constructing reinforced soil slopes is to increase the stability of the slope, particularly if a steeper than safe unreinforced slope is desirable or after a failure has already occurred (Elias et al. 2001). Soil reinforcement in embankments also provides improved compaction. Lateral resistance at the edges of a slope allows for increased compacted fill density over that otherwise achieved, and geosynthetics with in-plane drainage capabilities allow for rapid dissipation of compaction-induced pore pressures. Modest amounts of reinforcement in compacted slopes have also been found to decrease the tendency for surface sloughing and reduce slope erosion (Elias et al. 2001).

The design procedures for reinforced embankments are based on limiting equilibrium type analyses, which are similar to conventional bearing capacity or slope stability analyses (Holtz 1989). Stability calculations are made by assuming a series of potential sliding surfaces, as other methods, and the reinforcement acts as a horizontal force increasing the resisting moment. The resistance is mobilized primarily through interface friction. The method assumes a rigid, perfectly plastic stress-strain behavior and neglects effects of system deformation on the embankment-reinforcement interaction (Holtz 1989). The design requirements address the three following failure modes of reinforced slopes: (1) internal, where the failure plane passes through the reinforcing elements; (2) external, where the failure surface passes behind and underneath the reinforced mass; and (3) compound, where the failure plane passes behind and through the reinforced soil mass (Elias et al. 1998).

(a)

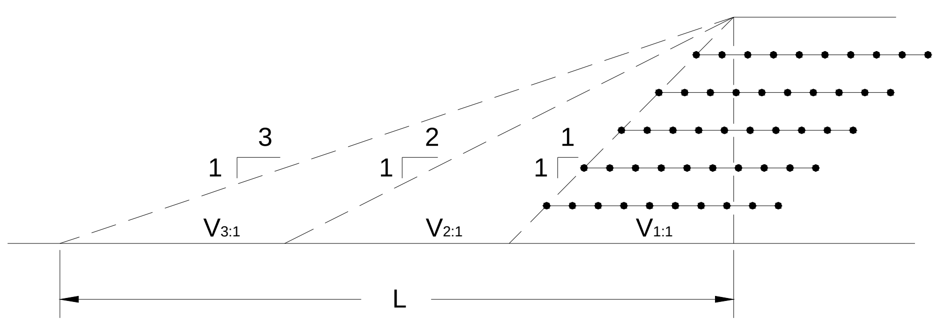
(b)

Figure 10. Construction of a reinforced soil slope on I-68 in West Virginia (photos courtesy of Jim Fisher)

The economy of reinforced soil slopes must be assessed on a case-by-case basis, where an appropriate benefit to cost ratio analysis should be carried out to see if the steeper slope with reinforcement is justified economically over the alternative flatter slope with its increased right-of-way and materials costs (Elias et al. 2001). The cost of constructing a reinforced soil slope depends on the cost of its primary components. Typical relative costs are the following (Elias et al. 2001):

- Reinforcement - 45 to 65 percent of total cost
- Backfill - 30 to 45 percent of total cost
- Face treatment - 5 to 10 percent of total cost

The relative cost of reinforcement generally increases with the height of reinforced soil slopes. Alternatively, backfill costs may decrease with increased slope heights. For applications in the 10 to 15 m (30 to 50 ft) height range, bid costs of approximately $170/m^2 ($16/ft^2) have been reported (Elias et al. 2001). A rapid, first-order assessment of cost items for comparing flatter unreinforced slopes with steeper reinforced slopes is provided in Figure 11.



$V_{3:1} = V$ $\qquad$ $V_{3:1} = L$

$V_{2:1} = bV$ $\qquad$ $V_{2:1} = bL$

$V_{1:1} = aV$ $\qquad$ $V_{1:1} = aL$

COST:

3H:1V = V_{SOIL} + L_{LAND} +Guardrail (?) + Hydroseeding (?)
2H:1V = bV_{SOIL} + bL_{LAND} +Guardrail + Erosion Control + High Maintenance
1H:1V = aV_{SOIL} + aL_{LAND} +Reinforcement + Guardrail + Erosion Control

Figure 11. Cost evaluation of reinforced soil slopes (reproduced from Elias et al. 2001)

Stone Columns

The Federal Highway Administration *Design and Construction of Stone Columns* by Barksdale and Bachus (1983) offers a complete source of technical data and specifications for highway applications, including embankment stabilization, bridge approach fills stabilization, bridge abutment and foundation support, and liquefaction mitigation.

Stone columns are vertical columns of compacted stone, and the reinforcement method can be used to increase the stability of both existing slopes and embankments constructed over soft ground (Barksdale and Bachus 1983). Stone column construction, shown in Figure 12, consists of the following steps:

1. Forming a vertical hole in the underlying material, using either the vibro-replacement or vibro-displacement technique.
2. Placing stone in the preformed hole from the ground surface, as in the vibro-replacement technique, or by means of bottom fee equipment, as in the vibro-displacement technique.
3. Compacting the stone by repenetration of each lift with the vibroflot, a process that drives the stone laterally to the sidewalls of the hole and thus enlarges the hole (Abramson et al. 2002).

Figure 12. Stone column construction at I-35/Hwy 5 in West Des Moines, Iowa (Pitt et al. 2003)

In using stone columns to stabilize slopes, 15 to 35 percent of weak or unsuitable material may be replaced by stone. The columns are generally less compressible than the matrix soil and exhibit higher shear strengths. The ground improvement technique increases the average shear resistance along potential failure surfaces which extend through the soil-column composite. Stone columns may also function as gravel drains, providing a path for relief of pore water pressures, thereby increasing the strength of the surrounding soils.

Stone columns may be economically attractive when required columns lengths are less than 30 ft (9 m). Approximate construction costs for a moderately-sized project (i.e., more than 8,000 linear ft of column) may range from $15 to $20/ft (Elias et al. 1998). The cost of stone, which is directly related to the distance between the stone source and the project, has been found to be approximately equal to the cost of construction.

In landslide applications, achieving sufficient normal stress on the stone columns to develop high shear resistance is sometimes a problem. A counterweight or berm can often be used to increase normal stress. Application of the berm also causes stress concentration in the column, which further increases its effectiveness (Barksdale and Bachus 1983). As the construction of a berm for the sole purpose of providing normal stress to the stone columns has negative environmental and economic consequences, the stone columns may be constructed within the embankment so the overburden soil increases the shear resistance of the stone columns for prevention of deep-seated failures.

Geopier Rammed Aggregate Piers

Geopier Rammed Aggregate Piers (RAPs) were originally developed to carry foundation loads and reduce settlement of the supported structures. Due to the unique construction process, rammed aggregate piers alter the post-construction properties of the matrix soil. Matrix soil is laterally prestressed and pier elements develop high strength and stiffness during construction (Wong et al. 2004). Currently, soil reinforcement with rammed aggregate piers is incorporated into the support of retaining walls and stabilization of highway embankments. Installation of rammed aggregate piers is shown in Figure 13.

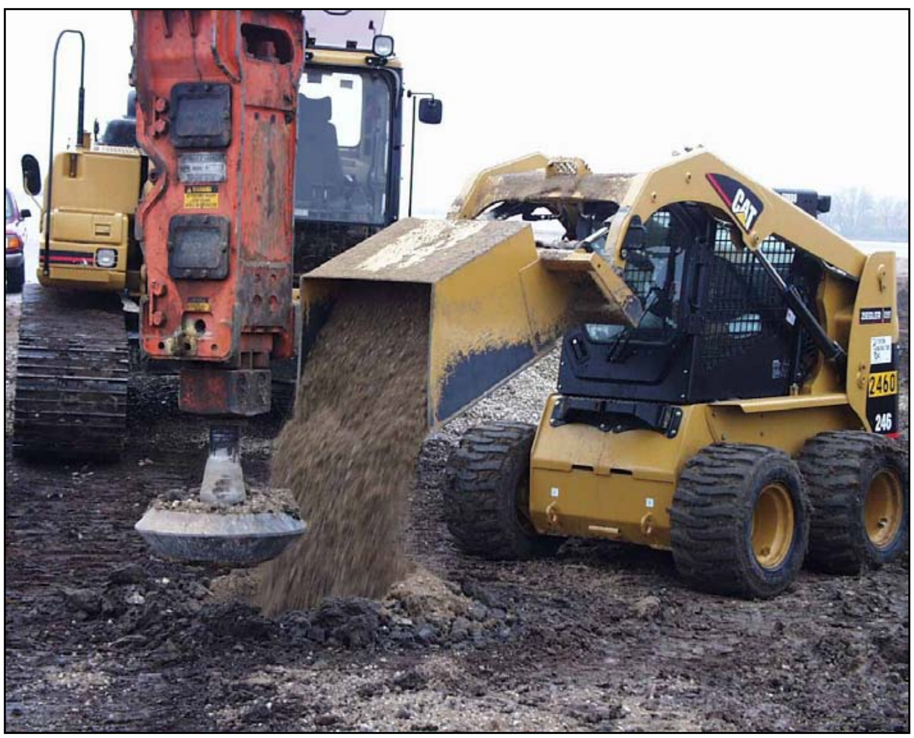


Figure 13. Rammed aggregate pier construction at I-35/Hwy 5 in West Des Moines, Iowa (Pitt et al. 2003)

Rammed aggregate piers are installed through potential failure surfaces to increase the shear strength parameter values (see Figure 14), increasing the factor of safety against sliding accordingly. Composite shear strength parameter values of the reinforced foundation soils are determined by calculating the weighted average of shear strength parameters of pier elements and matrix soil based on an areas ratio. Recognizing that the true cohesion intercept of the pier aggregate is approximately zero, and defining the area ratio (R_a) as the ratio of the area of the pier elements to the gross area of the reinforced zone ($R_a = A_p/A$), composite shear strength parameters for reinforced soil are determined with the following equations (Fox and Cowell 1998):

$$c_{comp} = c_m \cdot (1 - R_a) \tag{1}$$

$$\phi_{comp} = \tan^{-1}[R_a \tan\phi_g + (1 - R_a)\tan\phi_m] \tag{2}$$

where c_g and ϕ_g are the shear strength parameters of the aggregate, and c_m and ϕ_m are the shear strength parameters of the matrix soil. Axial loading of rammed aggregate piers results in stress concentration at pier tips, such that further increase in the composite shear strength is potentially employed for stability calculations. The average shear strength method, without considering the effect of stress concentration on shear strength, may often be overconservative and can adversely affect the economics of a project. Additional design detail for support of embankments using rammed aggregate piers is provided in White and Suleiman (2004).

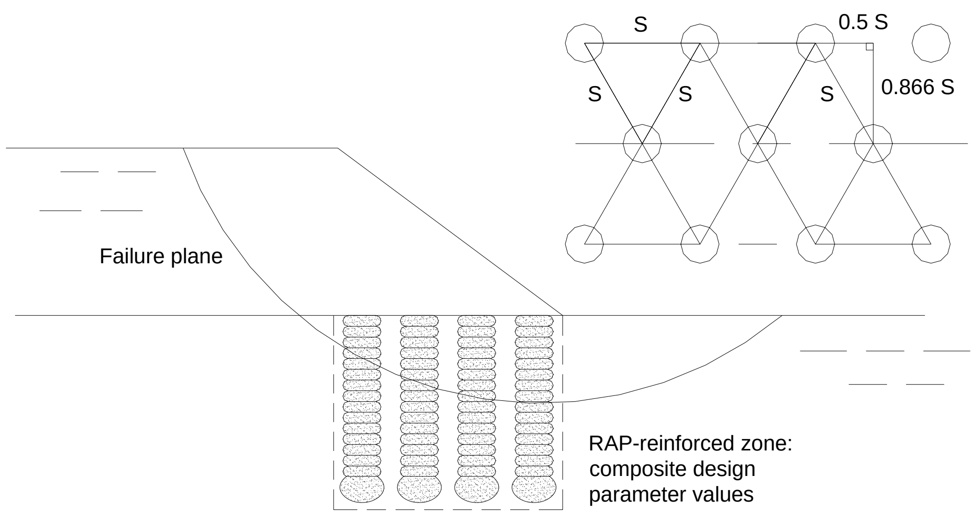


Figure 14. Slope stabilization with rammed aggregate piers

Field and laboratory tests (e.g., full-scale direct shear tests, triaxial shear tests) have shown the engineering properties of Geopier Rammed Aggregate Piers. Test results indicate a friction angle of approximately 49 degrees for piers constructed from open-graded stone and a friction angle of approximately 52 degrees for piers constructed from well-graded stone (Fox and Cowell 1998).

The economy of slope stabilization with Geopier Rammed Aggregate Piers depends on the specific variables of the project, as does slope stabilization with other remedial measures. The cost of installing a rammed aggregate pier primarily depends on soil type, slope geometry, pier length and spacing, and the total number of piers being installed. Generally, installation of one rammed aggregate pier costs approximately $400 to $600 or $3 to $6 per kN of column load.

Lime/Cement Columns and Deep Soil Mixing

Soil mixing and stabilization is an emerging technology, and the state-of-the-practice is summarized in the following reference:

- Federal Highway Administration. 1998. *Ground Improvement Technical Summaries, Vol. I*, FHWA-SA-98-086, Washington, DC.

Soil stabilization with chemical admixtures applies most commonly to the stabilization of roadway subgrades. More recently, however, equipment and procedures have been developed to apply and mix stabilizers in situ to make lime and cement columns, which have been successfully used to stabilize highway embankments on soft soils (Holtz 1989). The most feasible applications of lime/cement columns include improving the stability of natural slopes and excavations and reducing the settlements of shallow foundations.

The general term "lime" for soil stabilization refers to quicklime or hydrated lime, which are burned lime products as opposed to pulverized limestone (CMI 1994). For practice, lime may be applied in a powdered state, as slurry, or in pellet form. Cement is a hydraulic binder that, when mixed with water, sets and hardens for increased compression strength and improved load bearing capacity. Cement-stabilized soil is also known as "soil cement."

Lime reacts chemically and physically to yield particularly desirable results, most effectively with soils in the higher ranges of plasticity index (CMI 1994). Lime stabilization is feasible for inorganic clay soils, but its effectiveness decreases with increasing organic content (Holtz 1989). Silts are also difficult to stabilize with lime. Cement may be more appropriate to bind cohesionless and non-cohesive soils.

Lime, when introduced to soils containing clay minerals, initiate cation exchange and flocculation-agglomeration reactions. These first reactions cause immediate improvement of soil plasticity, workability, and uncured strength (Winterkorn and Pamukcu 1991). Continuing pozzolanic reactions result in time-dependent strength increase. Another important consequence of lime stabilization includes increased volumetric stability. For the case of cement stabilization, as the cement hydrates, a gel is formed that upon hardening forms strong bridges between aggregates (Winterkorn and Pamukcu 1991). Soil cement contains sufficient cement to produce a hard, durable, and structural material.

The influence of lime/cement columns on soil shear strength and embankment stability can be determined by calculating an average shear strength value for the stabilized soil through which potential failure surfaces extend, as follows (Abramson et al. 2002):

$$c_{avg} = c_u \cdot (1-a) + \frac{S_{col}}{a} \quad (3)$$

c_u = undrained shear strength of soil,
S_{col} = average shear strength of stabilized clay, and
a = relative column area $= \frac{\pi D^2}{4 S^2}$

Lime/cement columns are placed over a sufficiently large area of the slope, such that the composite shear strength parameter values result in a factor of safety which is greater than the target value. Additional stabilizing mechanisms of lime/cement columns, although more difficult to quantify, may include dehydration of clay, generation of negative pore water pressure, and lateral consolidation of the soil in the shear plane caused by column expansion (Rogers and Glendinning 1997). The installation of lime/cement columns is shown in Figure 15.

Figure 15. Lime/cement column installation

The normal stress acting on slip surfaces of shallow failures is usually of small magnitude. Consequently, a substantial increase in internal friction angle is required to increase the frictional resistance of the sliding soil. Small changes in the cohesion of soil, however, have a noticeable effect on the stability of the slope, such that the relatively large increase in cohesion of slope soils stabilized with lime columns adequately increases the factor of safety to resist slope movement. The remedial method for addressing slope instability typically requires that one third of the slope area be stabilized with lime columns.

Soil stabilization involves not only an increase in shear resistance and improvement of other physical properties of soil, but also the supply of a defense mechanism against adverse influences of continually changing environments (Winterkorn and Pamukcu 1991). Soil stabilization practices necessarily address daily and seasonal temperature and moisture changes, in addition to microbial and other biological activity.

Given the specialty equipment involved in deep soil mixing, minimum mobilization costs are approximately $100,000 (Elias et al. 1998). The cost for installing lime/cement columns depends on depth and type of in situ soil being treated, weather conditions, and project size. Deep soil mixing costs approximately $100 to $150 per cubic meter of treated soil for large projects. The cost may be only $60 per cubic meter for smaller projects with a reduced mobilization cost.

Soil Nailing

The soil nailing technology is fully documented in the following Federal Highway Administration reports:

- *Recommendations Clouterre*, FHWA-SA-93-068, 1994.
- *Soil Nailing for Stabilization of Highway Slopes and Excavations*, FHWA-RD-89-198, 1989.
- *Manual for Design and Construction Monitoring of Soil Nail Walls*, FHWA-SA-96-069, 1998.

Soil nailing is an in situ reinforcing technique for unstable soils (Elias and Juran 1991). The soil improvement method, most commonly used for stabilizing slopes or earth retaining structures, consists of drilling and grouting steel bars into a slope or cut face (see Figures 16 and 17). Inclusions act to reinforce the soil mass by transferring tensile and shear resistance of the nail to the soil (Steward 1994). Figure 18 illustrates how the soil load transfer to soil nails contributes to slope stability. The nails maintain the restraint force because they are anchored beyond potential failure surfaces. Fundamental soil nailing concepts are employed by multiple applications. Common applications of soil nailing include the stabilization of cut slopes, the retrofit of bridge abutments, and the excavation of earth retaining structures.

Figure 16. Installation of soil nails by drilling on I-235 in Iowa (from Makarla 2004)

Figure 17. Placement of steel inclusion in drilled hole on I-235 in Iowa (from Makarla 2004)

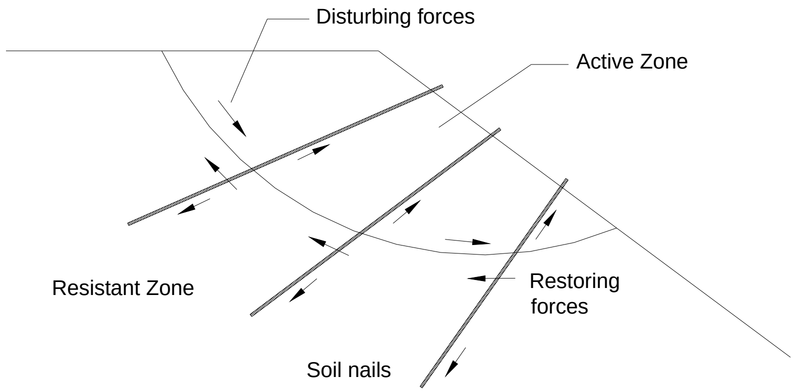


Figure 18. Soil nailing load transfer for slope stabilization (Steward 1994)

If installed in ground conditions well-suited for soil construction, soil nailing has proven to be a very economical method for stabilizing retaining walls and cut slopes. Soil nailing can provide 10 to 30 percent cost savings over permanent tieback walls or conventional cast-in-place walls with temporary shoring (Byrne et al. 1998). Additionally, cast-in-place or precast facings for permanent walls may be 40 to 50 percent of the total wall cost. As the facing is not necessary for stabilizing embankments or cut slopes, soil nailing as an alternative to stability berms is even more cost effective.

The bid data of 40 soil nailing projects are summarized in FHWA-SA-96-069, previously referenced. The mean unit cost from the highway projects was \$485 per m^2, with a standard deviation of \$210 per m^2. Limited information suggests that the cost for temporary wall construction ranges from \$160 to \$400 per m^2 (Elias et al. 1998).

Soil Nail Launching

Launched soil nailing, a technique developed in the United Kingdom by Soil Nailing Ltd. allows nails to be inserted into the slope using a launcher attached to the end of an excavator boom (Steward 1994). The launcher utilizes high pressure compressed air to install the nail, and the depth of penetration is controlled by both the compressed air pressure and the in situ material properties. Installation of launched soil nails is shown in Figure 19.

A number of methods can be used to account for the reinforcement benefit to the slope using launched soil nails. Soil Nailing Ltd. developed a design method using a simplified wedge analysis (Steward 1994). The soil nails impart both tensile and shear resistance from the nail to soil, as do traditional soil nails.

Traditional soil nailing includes a long delay time for the cement in the drilled holes to harden. Launched soil nails are effective immediately. The launcher can work in tandem with the primary excavation, resulting in little or no delay for other construction activities. Additionally, launched soil nails can be hollow and serve as horizontal drains. Multiple horizontal drains dry out the toe area, making it stronger. These launched horizontal drains are hollow steel bars and provide significantly increased tensile capacity in the toe area. The water and the pressure can be relieved with a dense array of launched horizontal drains in wet areas, seeps, and slide toes – anywhere water is not wanted.

Figure 19. Installation of soil nails with launcher (from soilnaillauncher.com)

After setup on the site, the launcher is capable of installing approximately 15 nails per hour. A cost range of $80 to $135 per nail is appropriate for an initial cost estimate for the launched soil nail repair alternative, including mobilization (Steward 1994). The total cost may, therefore, range from $300 to $600 per lineal foot, depending on the required level of remediation.

Pile Stabilization

Slope reinforcement with structural pile elements can be an effective slope remediation alternative when conventional remediation practices (e.g., improved drainage) fail to consider the causal factors leading to slope instability (e.g., strength loss due to weathering). Piles installed in failing slopes arrest or slow down the rate of slope movement. Slope movement induces lateral load distributions along stabilizing piles that vary with soil stiffness and strength, pile stiffness and section capacities, and the spacing of piles over the slope (White et al. 2005). Each pile element offers passive resistance to downslope soil movement by transferring the loads developed along the piles to stable soil below the failure surface. The use of piles to stabilize a slope is illustrated in Figure 20. Pile wall construction in West Virginia is shown in Figures 21 and 22.

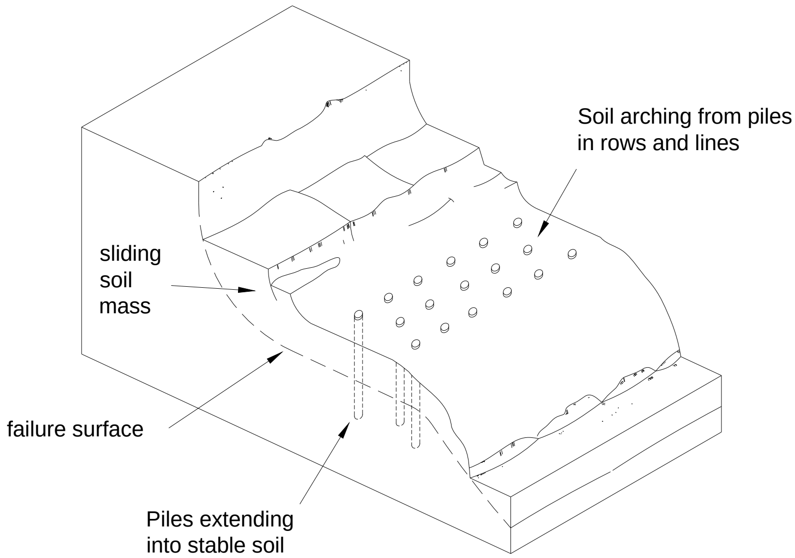


Figure 20. Illustration of pile-stabilized slope

Figure 21. Pile wall construction in West Virginia (photo courtesy of Jim Fisher)

Figure 22. Completed pile wall in West Virginia (photo courtesy of Jim Fisher)

The factors affecting pile performance under the loading conditions of slope reinforcement and the factors controlling the influence of piles on global slope stability are not yet fully understood. Complicating issues of pile-stabilized slopes may include the effects of (1) pile size and spacing, (2) pile orientation, (3) pile truncation, (4) soil arching, and (5) stress concentrations. The result of such uncertainties in the analysis of pile stabilization is the often overconservative design and uneconomical construction of the in situ reinforcement.

Slope stabilization with structural pile elements is nevertheless the focus of ongoing research. Recent investigations (e.g., Loehr et al. 2003; White et al. 2005) have evaluated the use of slender, “weak” reinforcing elements for stabilizing slopes. The newer methods may more effectively address the cost, environmental, schedule, and constructibility constraints of the remediation measure. The installation of recycled plastic pins is shown in Figure 23.

A design methodology for slope stabilization with pile elements, originally developed for recycled plastic pins, is presented in the following reference:

- *Slope Stabilization Using Recycled Plastic Pins*. 2003. Missouri DOT Report No. RDT 03-016.

Figure 23. Installation of recycled plastic pins (from Loehr and Bowders 2003)

Pile-Stabilized Platforms

Early use of piles to transfer the embankment load to more competent soils was reported to support bridge approaches and storage tanks (Reid and Buchanan 1983; Thornburn et al. 1983). Although using piles has many benefits, including rapid construction, minimization of settlement, reduction of right-of-way needs, and less maintenance (Hewlett and Randolph 1988), using reinforcement will maximize the economical benefits of the pile foundations. A wide range of pile types can be used under the embankments, including concrete (both driven and cast in place), stone columns, lime columns, deep mixing, vibro-concrete columns, timber piles, and Geopiers (see British Standard 1995).

The load transfer from embankment fill to the foundation elements in geosynthetic reinforced soil – pile supported (GRS – PS) embankments is a combination of soil arching effects in the embankment fill, a result of the stiffened platform, and stress concentration (Han and Wayne 2000). Further, the magnitude of load transfer is dependent on the number of reinforcement layers, tensile stiffness of the reinforcement, and shear strength properties of the embankment fill and foundation soils. The load transfer mechanisms are defined as follows:

1. Soil Arching Effect of Embankment Fill – Terzaghi (1943) defined arching effect as the transfer of pressure from a yielding mass of soil onto an adjoining stationary mass. As the soil mass above the subsoil moves relatively to the soil mass above the stationary pile, shearing stresses develop between the moving soil and the stationary soil mass causes a transfer of part of the weight of the fill to the piles (Terzaghi 1936).
2. Stress Concentration – The stiffness difference between a stiff pile unit and the soft foundation soil results in a higher vertical stress applied to the top of the piles than that applied to the soil.
3. Tension in the Reinforcement – Tension developed in the reinforcement is a result of strain developed from differential settlement between the foundation soil and the piles. As the tensile force increases in the reinforcement, a tensioned membrane effect helps support the overlying fill and transfers load to the piles.

Stress concentration ratio has been used as a global index that incorporates effects of soil arching, tension membrane, and pile-soil stiffness difference (Han and Wayne 2000).

The design of a reinforced piled embankment is different from that of a non-reinforced piled embankment and considers several failure conditions (see Figure 24). Pile group capacity and extent can be considered as in conventional pile design. Lateral sliding and the overall stability of the embankment can be evaluated using readily available limit equilibrium slope stability methods. Several design methods have been developed for GRS – PS embankments. The design process needs to consider (1) soil arching, (2) stress concentration or stress reduction ratio, (3) tension in geosynthetic reinforcement, (4) lateral sliding, (5) global and local slope stability, (6) pile head punching capacity, (7) settlement, (8) lateral deflection and maximum bending moment, and (9) loading (see British Standard 1995).

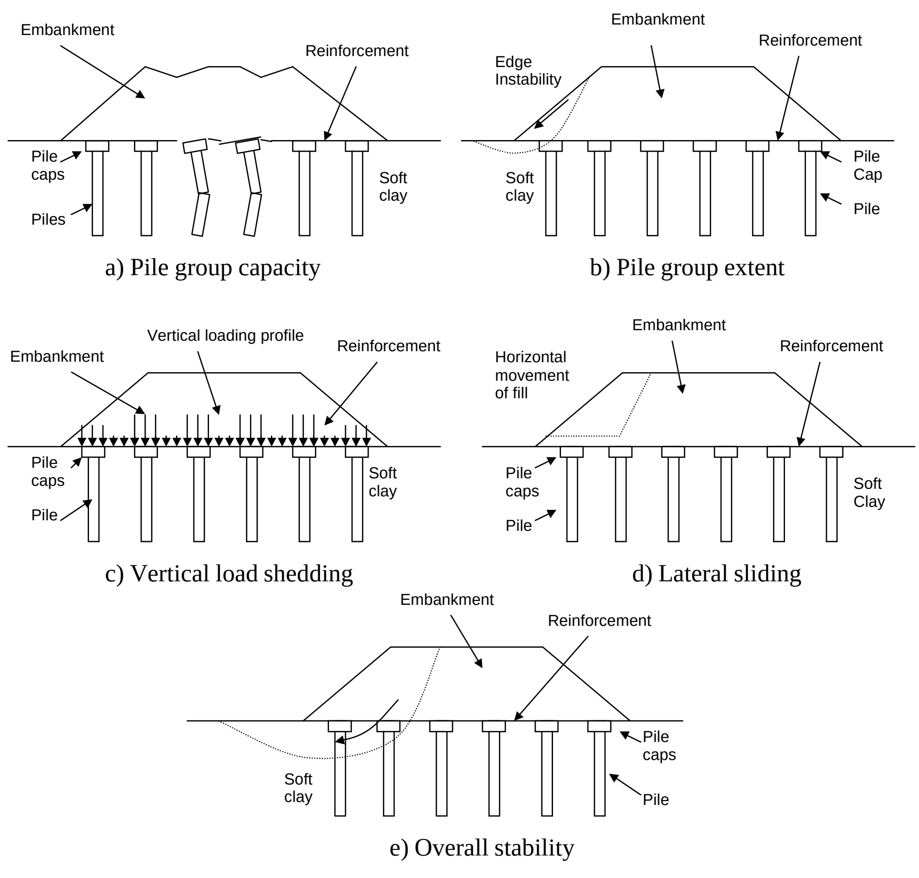


Figure 24. Ultimate limit states for basal reinforced piled embankments (from BS8006 1995)

Preloading and Wick Drains

Details of preloading and drainage for embankment slope stabilization are provided in the following reference:

- *Prefabricated Vertical Drains Vol. 1*. 1986. Federal Highway Administration Report No. FHWA-RD-86-168.

The application of vertical stresses to a deposit of saturated, cohesive foundation soil can result in three idealized settlement components (Rixner et al. 1986): (1) initial, (2) primary, and (3) secondary settlement. Initial settlement occurs during application of the load and is characterized by no volume change, such that vertical compression is accompanied by horizontal expansion. Primary consolidation occurs over time as drainage allows excess pore pressures to dissipate. The rate of primary consolidation depends principally on the volume change and permeability characteristics of the soil. Secondary compression is long-term settlement that occurs under constant effective stress and is usually of greatest concern with highly organic soils. For settlement analyses, the components presumably occur as separate processes.

Primary consolidation settlements generally predominate and are often the only settlements considered in a preload design. The preloading of foundation soils can be used to minimize post-construction settlements caused by primary consolidation. By surcharging, the technique in which the applied vertical load exceeds the final loading condition, the method can accelerate the precompression and can also reduce settlements due to secondary compression (Rixner et al. 1986).

If the foundation soils are weak relative to the applied preload, the preload design must also consider embankment and foundation stability. Slope flattening or controlling the rate of load application can mitigate the hazards associated with marginally stable slopes.

Vertical drains (e.g., wick drains) are installed in foundation soils to provide a drainage path for dissipation of excess pore pressure. By installing vertical drains throughout a site, drainage paths are effectively shortened and the rate of primary consolidation is accelerated. The installation of vertical drains is often accompanied by a preload. When used in conjunction with preloading, the primary benefits of a vertical drain system include (Rixner et al. 1986) (1) decreased time required for completion of primary consolidation due to preloading, (2) decreased amount of surcharge required to achieve the desired amount of precompression in the given time, and (3) increased rate of strength gain due to consolidation of soft soils when stability is of concern. Typical vertical drain installation for a highway embankment is illustrated in Figure 25.

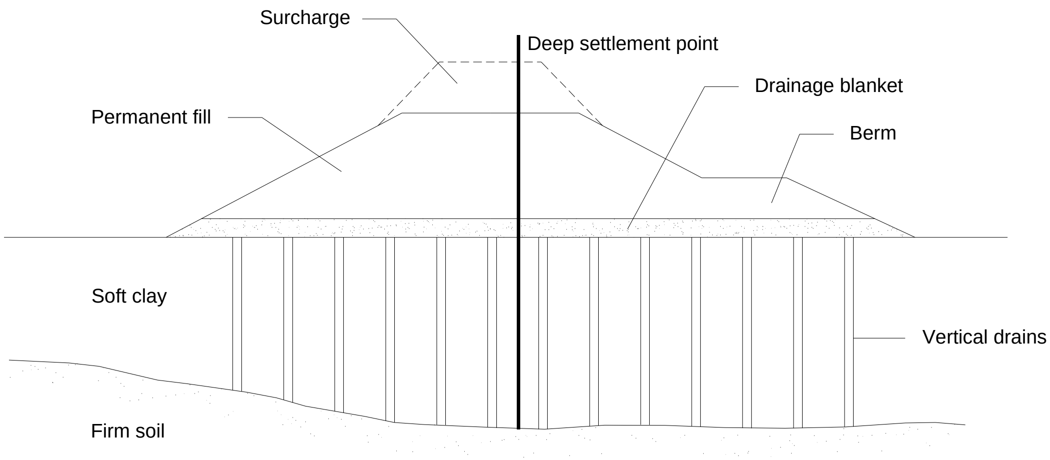


Figure 25. Typical vertical drain installation for highway embankment (Rixner 1986)

Typical costs for wick drain installation, assuming that no specialty equipment is needed to accommodate difficult penetration, are provided in Table 4.

Table 4. Typical wick drain installation costs (Elias et al. 1998)

Size Category	Unit Price Range Per m
Small (3,000 to 10,000 m)	$2.25 to $4.00
Medium (10,000 to 50,000 m)	$1.60 to $2.50
Large (> 50,000 m)	$0.90 to $1.60

SURVEY OF PRACTICE: STATE DOT STABILIZATION ALTERNATIVES

Questionnaires

A survey of geotechnical engineers at state departments of transportation was conducted to assess the frequency and cost effectiveness of the various stabilization alternatives. The survey also asked the respondents to specify whether the stabilization alternatives were employed to avoid the environmental impact associated with stability berms. Information provided by respondents was useful for inferring the effectiveness of each remedial measure, as the most frequently used and most cost effective alternatives generally offer the best solution. The questionnaire, provided in Appendix A, was prepared and sent to 170 engineers in all 50 states. Responses were received from 39 engineers, giving a response rate of 23 percent. Responses were received from 26 states. The questionnaire responses are provided in Appendix A. The percentages and average ratings presented herein are based solely on the information provided by the respondents.

Summary of Responses

An evaluation of the questionnaire responses shows that geotechnical engineers and state departments of transportation generally consider the environmental impact of their projects. The observation is based on 77 percent of respondents having used ground improvement techniques to eliminate embankment stability berms in environmentally sensitive areas. Due to the limited scope of the questionnaire, however, the results fail to indicate the motivation of taking such measures. The elimination of stability berms may be controlled by the regulatory environment of the state, or may be attributed to geotechnical and economy considerations of transportation management officials.

Remaining questions of the survey addressed the frequency of use and cost effectiveness of various stabilization technologies. Respondents were not asked to specify whether a technology was used for environmental protection or for remediation of general slope instability. For each technology, respondents applied a rating from 1 to 4. For assessing frequency of use, ratings were defined as follows: 1 = most common, 2 = frequent, 3 = seldom, and 4 = never. Similarly, ratings for evaluating the cost effectiveness of the methods were defined as: 1 = most cost effective, 2, 3, and 4 = least cost effective. Provided that comparable slope stabilization would be achieved with all methods, a trend for cost effectiveness was anticipated to resemble that for frequency of use. Departments of transportation are undoubtedly likely to utilize those methods that are simple, cheap, and effective.

The distribution of ratings for each stabilization technology is shown in Figure 26. To more easily compare the frequency of use and relative cost effectiveness of the stabilization technologies, average ratings were determined. The inverse of the average ratings were subsequently calculated, such that reported values range from 0.25 to 1.0 and higher values indicate more frequent and more cost-effective remedial methods. The comparison between remedial methods is provided in Figure 27.

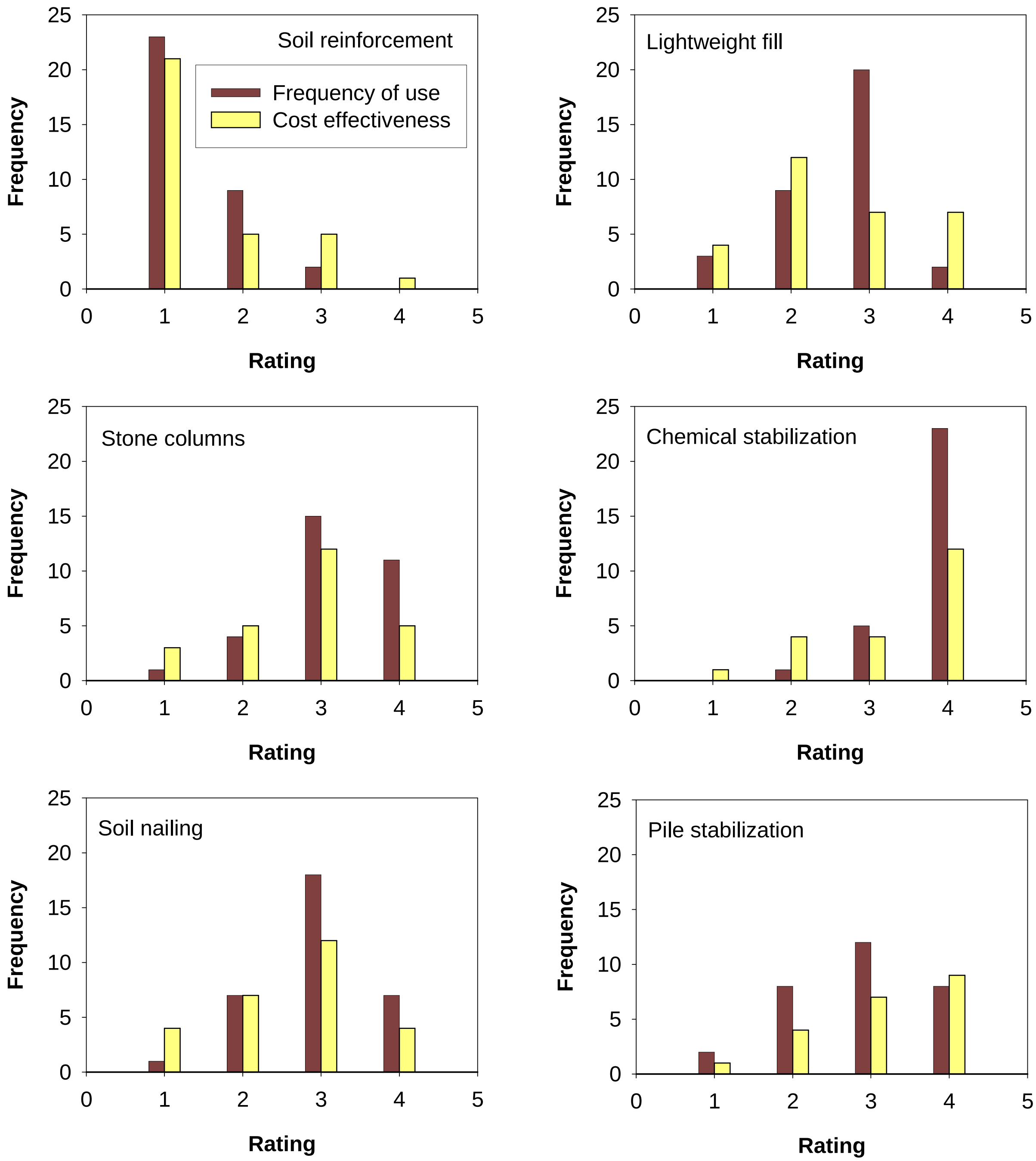


Figure 26. Distribution of responses

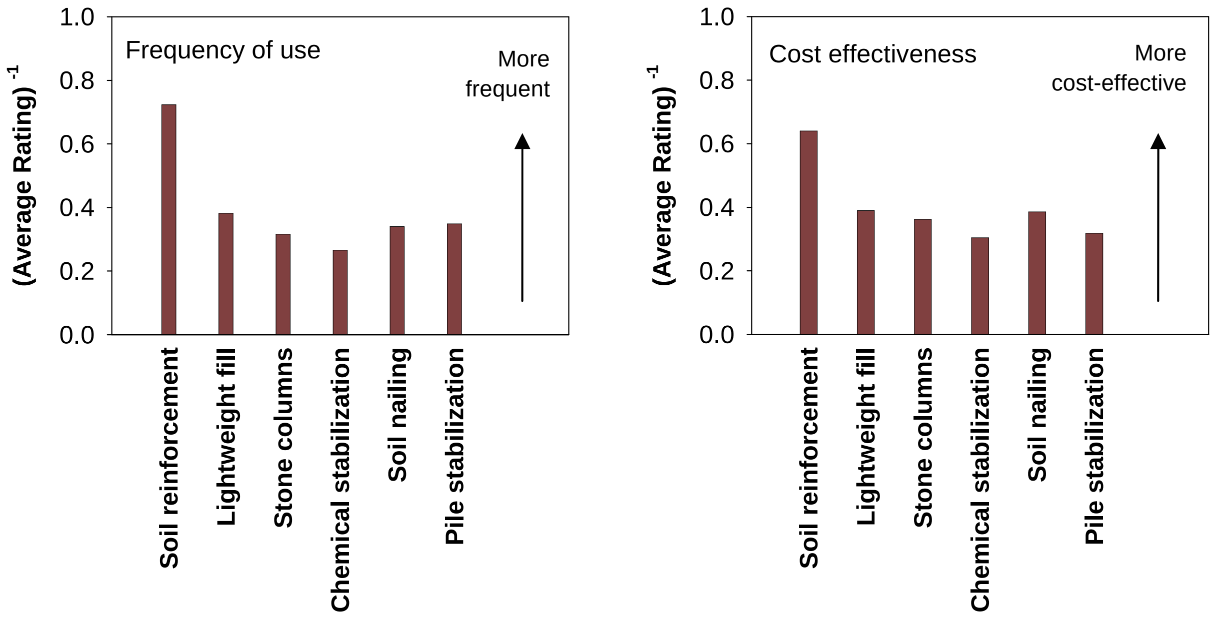


Figure 27. Response comparison between stabilization technologies

Geotechnical engineers overwhelmingly indicate that soil reinforcement (e.g., MSE walls and reinforced soil slopes) is the most common and most cost-effective solution for stabilizing cut slopes and embankments. Alternatively, chemical stabilization and installation of lime/cement columns is a remediation measure rarely employed by departments of transportation. Chemical stabilization of soil for slope stabilization may be considered a specialty remedial method, and the disadvantages of the technology involve performance that is dependent on environmental conditions and a lack of equipment and financial resources to make the alternative cost effective.

GUIDANCE IN STABILITY BERM ALTERNATIVE SELECTION

Geotechnical Considerations for Selecting Stability Berm Alternative

Given the array of technologies available for stabilizing slopes, seldom is there only one possible solution. Frequently, the most economical and effective means for treating unstable slopes consists of a combination of two or more of the stabilization technologies (Abramson et al. 2002). Determining the most economical and effective remedial measure can be complicated in and of itself. The process may be further complicated by other factors, including safety, construction scheduling, material availability, site accessibility, aesthetics, and of course environmental impact. Each of the factors must be acknowledged throughout the planning, design, and construction stages of a project.

Technical constraints of stabilization technologies may include ground conditions (e.g., soil type, location of groundwater), strain compatibility, in situ soil creep, or soil corrosivity (Abramson et al. 2002). The constraints do not necessarily apply to all remedial measures. Reinforced soil, for example, requires relatively large soil strains to mobilize strength of the geosynthetic system, such that large deformations of an embankment may be observed. Alternatively, corrosivity can adversely affect the long-term performance of steel-reinforced systems and concrete retaining walls.

The cause and nature of slope instability should be understood before corrective measures are undertaken, and the investigation of slope instability must recognize that several causes may exist simultaneously. At the same time, several embankment instabilities (e.g., rotational stability, bearing capacity, settlement) may need to be addressed by a single stabilization alternative. In this case, Table 5 can be used to determine which stabilization technologies address multiple modes of embankment failure. Installation of stone columns, for example, would support an embankment constructed on soft soils and would also increase global slope stability. The weight of the embankment would mobilize axial compression in the elements and transfer the load to a hard layer, while the area replacement of weak matrix soil with dense aggregate would result in improved shear strength along rotational failure surfaces. Stone columns could also be installed to control the rate of embankment settlement. The columns provide a path for dissipation of excess pore pressures, which further add to the stability of the embankment.

Table 5. Applications of soil reinforcement (Schlosser et al. 1979)

Application	Soil nailing	Micro-piles	Passive columns	Stone columns	Geo-synthetics	Anchors
Bearing capacity	X	X	---	X	X	---
Stability	X	X	X	X	X	X
Settlement magnitude	X	X	---	X	X	---
Settlement rate	---	---	---	X	---	---

Stabilization technologies may address excessive settlement and instability of highway slopes and embankments, as indicated above. Stability and settlement problems are often interrelated and time dependent (Ariema and Butler 1990). Finding the most appropriate procedure for ensuring stability and minimizing settlements requires an analysis of the various foundation treatment techniques, provided in Stabilization Technologies. Table 6 can be referenced to determine which stabilization technologies address stability and which technologies address settlement. The table also indicates the treatment methods which are time dependent.

Table 6. Foundation treatment alternatives (Holtz 1989)

Method	Variations of Method	Applicable to:		Time Dependent?		
		Stability Problems	Settlement Problems	Yes	No	Possibly
Berms; flatter slopes	---	X	---	---	X	---
Reduced stress method	Lightweight fill.	X	X	---	---	X
Pile-supported roadway	Elevated structure supported by piles driven into suitable bearing stratum.	X	X	---	X	---
	Swedish method of supporting embankment on piles driven into suitable bearing material. Piles have individual pile caps covering only a portion of base area of fill.	X	X	---	X	---
Removal of problem materials and replacement by suitable fill	Complete excavation of problem materials and replacement by suitable fill.	X	X	---	X	---
	Partial excavation (upper part) of soft material and replacement by suitable fill. No treatment of soft material not removed.	X	X	---	---	X
	Displacement of soft material by embankment weight, assisted by controlled excavation.	X	X	---	X	---
	Displacement of soft material by blasting, augmented by controlled placement of fill.	X	X	---	X	---

Table 6. (*continued*)

Method	Variations of Method	Applicable to:		Time Dependent?		
		Stability Problems	**Settlement Problems**	**Yes**	**No**	**Possibly**
Stabilization of soft materials by consolidation	Consolidation by surcharge only.	---	X	X	---	---
	Consolidation by surcharge combined with vertical drains to accelerate consolidation.	---	X	X	---	---
	Consolidation by surcharge combined with pressure relief wells or vertical drains along toe of fill.	---	X	X	---	---
Consolidation with paving delayed (stage construction)	Before paving, permit consolidation to occur under normal embankment loading without surcharge; accept postconstruction settlements.	---	X	X	---	---
Chemical alteration and stabilization	Lime and cement columns; grouting and injections; electro-osmosis; thermal; freezing; organic.	X	X	---	---	X
Physical alteration and stabilization; densification	Dynamic compaction (heavy tamping); blasting; vibrocompaction and vibroreplacement; sand compaction piles, stone columns; water.	X	X	---	X	---
Reinforcement	Geotextiles and geogrids; fascines; Wager short sheet piles; anchors; root piles.	X	---	---	X	---

Note: some combinations of methods are feasible.

Planning and Preliminary Design Processes for Embankments

The attitude of a particular highway agency toward performance requirements of new embankments will greatly influence design criteria and specified construction methods (Holtz 1989). A highway agency may request that minimal post-construction maintenance be necessary. The consequence of such a position is an increase in initial construction costs. Another highway agency may accept post-construction settlements, for example, provided the settlements are not detrimental to the function of the embankment. These agencies willingly assume reasonable post-construction maintenance and risk, concentrating initial resources on more advanced site investigation, testing, and design (Holtz 1989).

The initial stages of a project generally involve the development of potential stabilization schemes consisting of individual remedial methods or combinations of methods (Abramson et al. 2002). Slope stability analyses and conceptual designs are completed to aid calculation of a reasonably accurate cost estimate. Cost estimates should include costs for design, construction management, and contingencies. Each potential remedial measure has a potential outcome (e.g., success, failure). The probabilities of occurrence may be estimated using judgment, inspection and maintenance records, empirical methods, and/or rigorous methods. Additionally, the costs associated with a slope failure (e.g., clean-up, lost use of facility, property damage) may be estimated. Initial remediation costs, potential outcomes, and probable costs of a failure must be evaluated and balanced to achieve the best solution for the project.

Figure 28 was developed to incorporate the necessary tasks for selecting a stability berm alternative into general planning and preliminary design processes. The flow chart begins by identifying the need for slope stabilization, based on performance requirements of the engineered slope and environmental impact of conventional earthwork practices. As the feasibility of any stabilization technology depends on the project details and site-specific properties, site characterization is preferably performed prior to preliminary design of stabilization alternatives. The development of potential stabilization schemes then proceeds as previously discussed. The preliminary design of stabilization alternatives assesses initial costs, the potential for failure, and the cost of a failure. This information can be applied directly to risk management policies of the transportation agency, and the most appropriate remediation alternative can be selected.

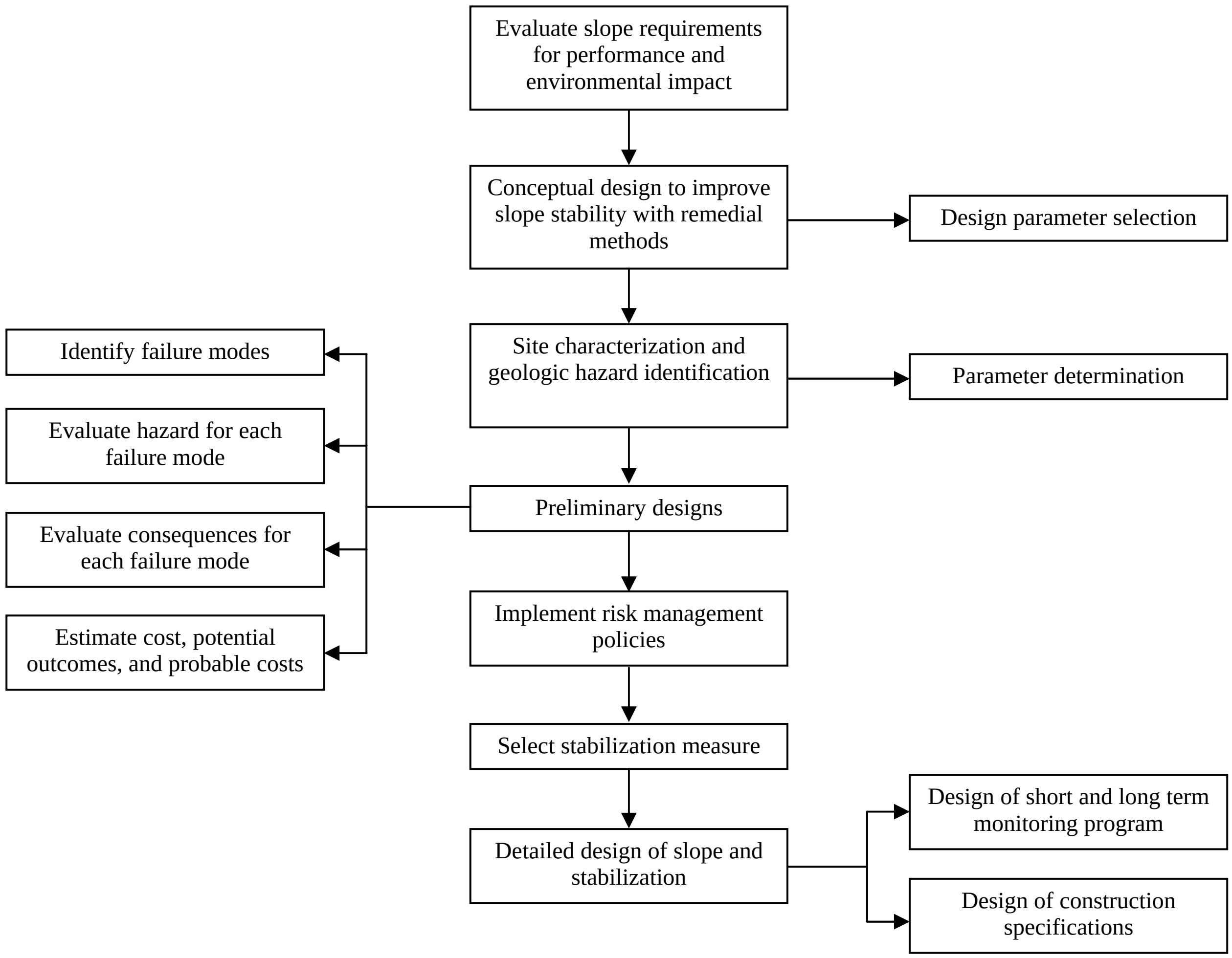


Figure 28. Flow chart for selecting and designing slope stabilization

FINAL REMARKS

The environmental impact of stability berms may be the principal motivation driving a transportation agency to design and construct engineered slopes that utilize alternative stabilization technologies. Initially, the cost of such slopes may exceed that corresponding to slopes stabilized with a stability berm. As the adverse environmental impact of stability berms is also a cost, a balance must be achieved to satisfy both environmental regulatory agencies and management officials of transportation agencies. The problem of balancing initial costs with environmental benefit has consequences which extend beyond geotechnical considerations of the engineered slopes. From a geotechnical perspective, however, slope stabilization becomes more reliably constructed, more competitively bid, and thus more cost-efficient when transportation agencies begin to more frequently design stabilization using alternative remedial methods.

State departments of transportation are becoming increasingly concerned about the environmental impact of their projects, as evidenced by survey results. As a result, the transportation agencies are showing increased motivation in assuring slope stability by methods other than use of stability berms. Soil reinforcement with geosynthetics is the most frequently used and cost-effective method for building steeper slopes in areas of limited right-of-way or limited environmentally-acceptable footprint area. The remaining stabilization alternatives show varying frequency of use, a product of varying cost and certainty of the methods. Several of the stabilization technologies are presently in the experimental phase of development (e.g., lightweight fill materials, pile stabilization), and further research is needed before the technologies can become standard practice for achieving slope stability.

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APPENDIX A: QUESTIONNAIRE AND RESPONSES

Iowa Department of Transportation

Research Project CSMR(5) - 90 - 00
Review of Stability Berm Alternatives for Environmentally Sensitive Areas

Questionnaire completed by: ______________________ Organization: _______________________

Address: ______________________________________ Email: _____________________________
____
____

1. Have you or your consultants used ground improvement/reinforcement techniques to eliminate embankment stability berms in environmentally sensitive areas?

_____ Yes
_____ No

2. What ground improvement/reinforcement methods have you or your consultants used to ensure global stability of potentially unstable cut slopes or new embankments?

Please rank using: 1 = most common, 2 = frequent, 3 = Seldom a factor, 4 = Never

_____ Soil reinforcement: MSE walls or geogrid-reinforced soil slopes
_____ Lightweight fill methods (e.g. geofoam applications, shredded tires)
_____ Stone columns or *Geopier* rammed aggregate piers
_____ Chemical stabilization (e.g. lime stabilization, lime/cement columns)
_____ Soil nailing
_____ Pile stabilization (i.e. spaced drilled piers or micropiles)
_____ Other, please explain:
____
____

3. In your opinion, what methods are most cost-effective?

Please rank using: 1 = most cost effective, 2, 3, 4 = least cost effective

_____ Lightweight fill methods (e.g. geofoam applications, shredded tires)
_____ Stone columns or *Geopier* rammed aggregate piers
_____ Chemical stabilization (e.g. lime stabilization, lime/cement columns)
_____ Soil nailing
_____ Soil reinforcement: MSE walls or geogrid-reinforced soil slopes
_____ Geosynthetic pile reinforced embankments
_____ Other, please explain:
____
____

4. Are you or your consultants willing to share design details and/or pictures of embankment stabilization projects?

_____ Yes
_____ No

5. Additional comments:
____
____

Table A.1. Summary of questionnaire responses

Question		AK	AL	AL	AL	CA	CA	CT	GA	IA	ID
Use of stability berm alternatives:		No	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
Frequency of use:	Soil reinforcement	-	1	2	1	2	1	1	1	2	1
1 to 4,	Lightweight fill	-	3	3	3	2	3	2	3	3	3
1 = most common	Stone column/Geopier RAP	-	3	4	3	3	2	4	4	2	3
	Chemical stabilization	-	4	3	4	4	3	4	4	4	-
	Soil nailing	-	3	3	2	2	1	4	2	3	2
	Pile stabilization	-	-	3	3	3	1	2	3	2	-
Cost effectiveness:	Soil reinforcement	-	1	-	1	1	1	-	3	3	1
1 to 4,	Lightweight fill	-	-	-	4	1	4	-	4	4	3
1 = most cost effective	Stone column/Geopier RAP	-	-	-	3	1	1	-	3	3	4
	Chemical stabilization	-	-	-	2	4	2	-	2	3	-
	Soil nailing	-	-	-	2	1	1	-	3	3	3
	Pile stabilization	-	-	-	3	3	1	-	4	2	-

Table A.1. (*continued*)

Question		IL	IN	KS	MA	MA	MD	MI	MN	MT	ND
Use of stability berm alternatives:		No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Frequency of use:	Soil reinforcement	2	-	1	1	1	1	2	2	1	-
1 to 4,	Lightweight fill	3	-	2	3	3	3	1	1	3	-
1 = most common	Stone column/Geopier RAP	3	-	1	3	-	2	3	3	-	-
	Chemical stabilization	4	-	2	4	-	-	4	4	-	-
	Soil nailing	2	-	3	3	-	4	4	3	2	-
	Pile stabilization	2	-	4	2	-	4	4	3	4	-
Cost effectiveness:	Soil reinforcement	1	-	1	1	1	2	1	2	1	-
1 to 4,	Lightweight fill	4	-	2	2	3	3	1	3	3	-
1 = most cost effective	Stone column/Geopier RAP	3	-	1	2	-	2	3	3	3	-
	Chemical stabilization	3	-	4	4	-	-	3	4	4	-
	Soil nailing	2	-	1	3	-	4	4	3	2	-
	Pile stabilization	-	-	-	3	-	4	2	2	4	-

Table A.1. (*continued*)

Question		**NY**	**NY**	**OR**	**OR**	**OR**	**OR**	**RI**	**SC**	**SD**	**SD**
Use of stability berm alternatives:		Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Frequency of use:	Soil reinforcement	1	2	-	1	1	1	1	1	3	-
1 to 4,	Lightweight fill	2	1	-	3	4	3	3	3	4	-
1 = most common	Stone column/Geopier RAP	3	3	-	3	4	4	4	2	4	-
	Chemical stabilization	4	4	-	4	4	4	3	4	4	-
	Soil nailing	3	3	-	3	3	3	3	4	4	-
	Pile stabilization	4	3	-	3	2	3	3	2	4	-
Cost effectiveness:	Soil reinforcement	2	1	-	1	1	1	3	1	1	-
1 to 4,	Lightweight fill	2	1	-	2	2	3	1	2	-	-
1 = most cost effective	Stone column/Geopier RAP	2	3	-	3	4	4	-	2	-	-
	Chemical stabilization	4	4	-	4	-	3	-	-	-	-
	Soil nailing	3	3	-	2	3	3	2	-	-	-
	Pile stabilization	4	4	-	4	-	3	-	2	-	-

Table A.1. (continued)

Question		UT	WA	WI	WV	WY	WY	WY	WY	WY
Use of stability berm alternatives:		No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Frequency of use:	Soil reinforcement	3	1	1	2	1	1	1	1	2
1 to 4,	Lightweight fill	3	2	3	2	3	2	2	2	3
1 = most common	Stone column/Geopier RAP	3	3	3	3	4	4	4	4	-
	Chemical stabilization	4	3	4	3	4	4	4	4	-
	Soil nailing	3	3	4	4	2	3	3	3	3
	Pile stabilization	4	3	4	1	2	3	2	3	-
Cost effectiveness:	Soil reinforcement	3	1	2	4	3	1	1	2	1
1 to 4,	Lightweight fill	2	2	4	2	4	3	2	2	2
1 = most cost effective	Stone column/Geopier RAP	3	3	3	-	2	4	4	-	-
	Chemical stabilization	-	4	4	1	2	4	4	-	-
	Soil nailing	2	4	4	-	1	2	3	3	3
	Pile stabilization	-	4	4	3	4	3	3	-	-

Table A.2. Additional comments from questionnaire responses

State	Comments (Other Remedial Measures)
AK	Flatten Slopes
AL	We have a couple of projects in which we are utilizing Lighweight fill and soil nailing.
AL	Use of geogrid rather than complete soft soil removal is often done in marshy areas.
	We have used a number of the techniques you describe above, reinforced soil slopes, drilled shafts, soil nailing, MSE walls, and geofaom, for general construction which, while they aid in lessening environmental impacts, were not used primarily for environmental concerns. It was obviously one of the benefits that occurred because of the use of the described techniques. Relative to question 4, it will be difficult to compare cost because not all applications can be used for the same conditions, which effectively controls the cost.
AL	Removal of soft soil material and replacement with A-4 or better material
CA	band drains (i.e., "wick drains")
CT	Depends on the site and the soil conditions...we are not married to any one particular solution. All are evaluated and the most cost-effective, viable solution is chosen....
GA	Embankment stabilized with filter fabric and staged construction
IA	Core-outs; stability berms in rural areas; drainage systems (all where possible)
ID	Prefabricated vertical drains (wick drains) to accelerate consolidation and strength gain of foundation soils

IL	What's "environmentally sensitive" areas? Normally, depending on availability of ROW, we prefer the relatively least expensive procedure of removal and replacement (with suitable material) for relatively shallow problem soils, under new embankment, and erosion control measures for cut slopes
MA	Excavate and replace, particularly peat
MD	We have used the removal and replacement technique, Dynamic deep compaction, Wick Drain and Slope drain.
MN	Horizontal drains, staged loading, prefab. vertical ('wick') drains and profile/alignment adjustments. Each job is a little different, the risk tolerance is often the key factor in selecting an option. Beyond simple risk is what the District can accept for a successful project, i.e., gradual dip of small crack OK vs. must be perfect. We are also in the design stages of recommending launched soil nails. Best of luck in your work. Your friends to the north.
MT	For most cases of embankments on soft foundations, earthen stability berms remain by far the most cost effective, method to stabilize the embankment. The environmental agencies and decision makers should be aware of the additional cost(often considerable) of utilizing the other methods presented above. These methods are not new, and in most cases have been around 20 to 30 years.
NY	Drainage methods (e.g., horizontal drains, stone trenches), preloading (with or w/o wick drains), shear keys, bio-engineering methods (for cut slopes). In many cases horizontal drains are most cost effective for marginally stable slopes (although not necessarily most effective from an engineering standpoint).
OR	Rock bolts
OR	wick drains, subexcavation/replacement, staged embankment construction (perhaps with wick drains), tieback walls.

WA	In environmentally sensitive areas our goal to stay out of the wetland or marked area. Using stone columns or chemical methods usually involves work outside the embankment toe. This is usually not acceptable to permitting agencies, and thus we do not use these methods in environmentally sensitive areas.
WI	Remove and replace poor soils, Perform staged construction, Use walls other than MSE
WV	We have used lime stabilization one time to my knowledge. We also will be using stone columns for the first time on one of our projects. We have installed a lot of piling walls and MSE walls. We are just starting to use reinforced soil slopes. We have built two reinforced soil slopes and scheduled to construct at least two additional slopes this construction season. We have never used soil nailing on any of our projects. We have never used shredded tires or geofoam in our fills. We have used elastizell behind our retaining wall. We have looked at geofoam before, but it wasn't used. We have used Bottom Ash before in our embankments and backfill for our retaining walls. Bottom ash has a dry density of 60-80 lbs/cu ft. I think MSE walls and geogrid reinforced soil slopes should be separated out. We our looking at reinforced soil slopes instead of MSE walls because they are cheaper than MSE walls.
WY	Dirt toe berms have worked best for us, and are cheap
WY	Tie Back Anchors
WY	Also consider deep soil mixing I am on the pooled fund study for deep soil mixing. Guidlines and construction manual will be out within the next year or so. Although expensive, this would be a very viable remediation method in sensitive areas.
WY	pile stabilization was actually driven "H" piles

APPENDIX B: SUPPLEMENTAL REFERENCES

A separate document contains supplemental literature, which can be consulted for additional information regarding design procedures, construction details, or research results. This reference material is submitted separately from the report and is comprised of excerpts of research reports, design manuals, and text books.