Guidelines for Geofoam Applications in Slope Stability Projects

DETAILS

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AUTHORS

Arellano, David; Stark, Timothy D.; Horvath, John S.; and Leshchinsky, Dov

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GUIDELINES FOR GEOFOAM APPLICATIONS IN SLOPE STABILITY PROJECTS

This digest presents the results of NCHRP Project 24-11(02), "Guidelines for Geofoam Applications in Slope Stability Projects." The research was performed by the Department of Civil Engineering at The University of Memphis (UoM). David Arellano, Associate Professor of Civil Engineering at UoM, was the Project Director. The other project investigators were Timothy D. Stark, Professor and Consulting Engineer, Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign; John S. Horvath, Consulting Engineer and Professor, Civil and Environmental Engineering Department at Manhattan College; and Dov Leshchinsky, President of ADAMA Engineering, Inc., and Professor, Department of Civil and Environmental Engineering at the University of Delaware. The contractor's final report for NCHRP Project 24-11(02) can be accessed via TRB.org/NCHRP by linking to the project page.

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INTRODUCTION

Geofoam is any manufactured material created by an internal expansion process that results in a material with a texture of numerous, closed, gas-filled cells using either a fixed plant or an in situ expansion process (Horvath, 1995). From a technical and cost perspective, the most successful and predominant geofoam material used as lightweight fill in road construction is expanded polystyrene-block (EPS-block) geofoam.

Geofoam is considered a type or category of geosynthetic. As with most types of geosynthetics, geofoam can provide a wide variety of functions including thermal insulation, lightweight fill, compressible inclusion, fluid transmission (drainage), damping, low earth pressure fill for retaining structures, and structural support. Each of these functions may have numerous potential applications. Although the focus of the present study is on the geofoam function of *lightweight fill*, the specific application of this function is slope stabilization and remediation of roadway embankments subjected to slope instability. The fact that geofoam can provide other functions—even if not intended or not necessarily desired in a particular project—should be considered in the design of geofoam for lightweight fills in road embankments. For example, in addition to the lightweight fill function, the functions of structural support and thermal insulation should be considered during the use of EPS-block geofoam as a lightweight fill material in slope stabilization and repair.

The first project to use block-molded EPS as a lightweight fill material is the Flom Bridge project in Norway in 1972. The EPS-block geofoam was used to rebuild a road over soft soil that had chronic settlement problems. In Europe, lightweight fills such as EPS-block geofoam are routinely used to construct embankments over soft foundation soils. In Japan, EPS-block

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geofoam is also extensively used for lightweight fill applications including in slope applications. Significant research and development of the use of EPS-block geofoam has been performed in Japan for seismic loading applications (Horvath, 1999).

Although EPS-block geofoam for road construction is an established technology and despite the more than 30 years of extensive and continuing worldwide use of EPS-block geofoam, it has been underutilized in U.S. practice because a comprehensive design guideline for its use as lightweight fill in roadway embankments has been unavailable. There was, therefore, a need in the United States to develop formal and detailed design documents for use of EPS-block geofoam in roadway applications.

To meet this need, the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration (FHWA), funded NCHRP Project 24-11(01), "Guidelines for Geofoam Applications in Embankment Projects." Conducted from July 6, 1999 to August 31, 2002, this research project's objective was to develop a recommended design guideline and a material and construction standard for the use of EPS-block geofoam in stand-alone embankments and bridge approaches over soft ground.

The results of this NCHRP project are presented in two documents. *NCHRP Report 529* includes only the recommended design guideline and the recommended material and construction for use of geofoam in stand-alone roadway embankments standard (Stark et al., 2004a). *NCHRP Web Document 65* includes the background and analyses used to develop the recommended design guideline and the material and construction standard, as well as a summary of the engineering properties of EPS-block geofoam and an economic analysis of geofoam versus other lightweight fill materials (Stark et al., 2004b).

EPS-block geofoam is unique as a lightweight fill material because it has a unit weight that is only about 1% of the unit weight of traditional earth fill materials and that is also substantially less than other types of lightweight fills (16 kg/m^3 or 1 lb/ft^3 versus 1,900 kg/m^3 or 120 lb/ft^3). In addition, geofoam is sufficiently strong to support heavy motor vehicles, trains, airplanes, lightly loaded buildings, and the abutments of bridges, if designed properly. The extraordinarily low unit weight of EPS-block geofoam results in significantly reduced gravity stresses on underlying foundation soils as well as reduced inertial forces during seismic shaking. Thus, the lower density of EPS-block geofoam may alleviate the costs of soft soil removal (which include the attendant disposal problems and costs); soil improvement techniques; and/or the possible need for an excavation support system, excavation widening, and extensive temporary dewatering.

An example of the extensive use of the NCHRP Project 24-11(01) reports is the large use of EPS-block geofoam on the Central Artery/Tunnel (CA/T) project in Boston. This project is the first major project to use the NCHRP Project 24-11(01) research results in practice (Riad, 2005). Another project that used the NCHRP research results is the I-95/Route 1 Interchange (Woodrow Wilson Bridge Replacement) in Alexandria, VA. These and other projects that have been completed in the United States (e.g., the I-15 Reconstruction Project in Salt Lake City) demonstrate that EPS-block geofoam is a technically viable and cost-effective alternative to the construction or remediation of stand-alone embankments over soft ground. Additionally, Thompson and White (2005) conclude that EPS-block geofoam may be a stabilization technology that can be used as an alternative to the use of stability berms to minimize the impacts to environmentally sensitive areas where embankments cross soft or unstable ground conditions.

FHWA has designated EPS-block geofoam as a priority, market-ready technology with a deployment goal that EPS geofoam will be a routinely used lightweight fill alternative on projects where the construction schedule is of concern (FHWA, 2006). FHWA considers EPS-block geofoam an innovative material and construction technique that can accelerate project schedules by reducing vertical stress on the underlying soil; thus, it is a viable and cost-effective solution to roadway embankment widening and new roadway embankment alignments over soft ground. In summary, EPS-block geofoam is a market-ready technology that can contribute to solving the major highway problem in the United States of insufficient highway capacity to meet growing demand.

PROBLEM STATEMENT

A major transportation problem in the United States is that current highway capacity is insufficient to meet growing demand; therefore, new roadway alignments and/or widening of existing roadway embankments will be required to solve the current and future highway capacity problem. As noted by Spiker and Gori (2003), roadway construction "often exacerbates the landslide problem in hilly areas by altering the landscape, slopes, and drainages and by changing and channeling runoff, thereby increasing the potential for landslides." Landslides occur in every state and U.S. territory, especially in the Pacific Coast, the Rocky Mountains, the Appalachian Mountains, and Puerto Rico (Spiker and Gori, 2003; TRB, 1996). Active seismic activity contributes to the landslide hazard risk in areas such as Alaska, Hawaii, and the Pacific Coast. Spiker and Gori indicate that landslides are among the most widespread geologic hazard on earth and estimate that damages related to landslides exceed $2 billion annually.

An additional application of EPS-block geofoam as a lightweight fill that has not been extensively utilized in the United States, but has been commonly used in Japan, is in slope stabilization. The decades of experience in countries such as Norway and Japan with both soft ground and mountainous terrain have demonstrated the efficacy of using the lightweight fill function of EPS-block geofoam in both stand-alone embankments over soft ground and slope stabilization applications. The Japanese experience has also involved the use of EPS-block geofoam when severe seismic loading is a design criterion.

The recommended design guideline and the standard included in the NCHRP Project 24-11(01) reports are limited to stand-alone embankments and bridge approaches over soft ground. The experience in Japan has demonstrated that there are important analysis and design differences between the lightweight fill function for stand-alone embankments over soft ground and slope stabilization applications. Therefore, a need exists in the United States to develop formal and detailed design documents for use of EPS-block geofoam for slope stabilization projects. Slope stabilization projects include new roadways as well as repair of existing roadways that have been damaged by slope instability or slope movement. This need resulted in the current NCHRP Project 24-11(02), the results of which are summarized herein.

SOLUTION ALTERNATIVES

Slope stability represents one of the most complex and challenging problems within the practice of geotechnical engineering. The unique challenges presented by the interactions between groundwater and earth materials, the complexities of shear strength in earth materials, and the variable nature of earth materials and slope loadings can combine to make the successful design of a stable slope difficult, even for an experienced engineer. Over the years, a wide variety of slope stabilization and repair techniques have been used in both natural and constructed slopes. When implementing a slope stabilization and repair design, the strategy employed by the designer can usually be classified as (1) avoid the problem altogether, (2) reduce the driving forces, or (3) increase the resisting forces.

For any given project, the option of avoiding the problem is generally the simplest solution; however, it is typically not a feasible option, especially for roadways. In many cases, selecting an alternate site or removing and replacing the problematic earth material are simply not viable options. This leaves designers with a choice between the remaining two strategies for constructing a stable slope. The resisting forces may be accepted as they are and the design may be based on reducing the forces that drive instability, or, conversely, the driving forces may be accepted as they are and the design may be based on improving the resisting forces sufficiently to prevent failure of the slope.

Some of the more common design alternatives to increase the resisting forces of a slope include the installation of deep foundations—for example, piles and drilled shafts—or other type of reinforcing material to assist in restraining the unstable slope material; the construction of "toe berms" to add weight to the bottom portion of the slope; chemical or biotechnical soil improvement methods that increase the strength of earth materials; and/or the installation of subsurface drainage to divert groundwater away from the slope and increase the effective stress, which increases the soil resisting forces. Many of these procedures can be costly, both in terms of actual installation costs, as well as other indirect costs such as prolonged road closures, acquisition of additional right-of-way for the new construction, and long-term maintenance costs. However, some of these procedures do have the advantage of having a relatively long history of successful application. In many cases, designers and contractors are somewhat familiar with the approaches being used, enabling them to work more efficiently when using a well-established technology.

The simplest solution to reducing the driving forces within a slope is simply to reduce the slope inclination. This reduces the shear stress on the material in the slope, making the entire slope more stable. However, the costs of pursuing this solution can be considerable, including right-of-way acquisition, earth material removal costs, and lane or road closures during construction. For many slopes, particularly those in urban settings, flattening the slope is simply not a feasible option. Other alternatives that serve to reduce driving forces could be the installation of subsurface drainage (which can serve both to increase resisting forces and to reduce driving forces), installation of better surface drainage to reduce infiltration from storm water accumulation, and replacement of a portion of the natural slope material with lightweight fill.

The latter alternative to reducing the driving forces may encompass a wide variety of materials, both natural and man-made, that can significantly reduce the weight of the upper portion of the slope, thus reducing driving forces that tend to cause slope instability. A wide range of lightweight fill materials—such as shredded tires, wood fiber, saw dust, ash, pumice, air-foamed stabilized soil, expanded-beads mixed with soil, and EPS-block geofoam—have been successfully used as lightweight fill both in the United States and globally. As might be expected, each type of lightweight fill has its own unique advantages and disadvantages that must be considered when evaluating alternatives for any design. The purpose of this project is to provide guidance for slope stabilization and repair utilizing EPS-block geofoam as a lightweight fill material.

RESEARCH OBJECTIVE

The overall objective of this research was to develop a comprehensive document that provides both state-of-the-art knowledge and state-of-practice design guidance to those who have primary involvement with roadway embankment projects with design guidance for use of EPS-block geofoam in slope stability applications. The end users of the research include design professionals such as engineers who perform the design and develop specifications; owners including FHWA, state DOTs, and local county and city transportation departments that own, operate, and maintain the roadway; the manufacturers/suppliers who supply EPS blocks; and the contractors who construct the roadway.

The general consensus that was reached at the first *International Workshop on Lightweight Geo-Materials* that was held on March 26 and 27, 2002, in Tokyo is that although new weight-reduction techniques for decreasing applied loads have recently been developed, standardization of design and construction methods is still required ("A Report on the *International Workshop on Lightweight Geo-Materials,*" 2002). The research results from NCHRP Project 24-11(01) in conjunction with the results of this project standardize the design guidelines for the use of EPS-block geofoam in various U.S. highway applications.

KEY RESEARCH PRODUCTS

Successful technology transfer and acceptance of a construction product or technique requires the availability of a comprehensive and useful design procedure and a material and construction standard. Additionally, knowledge of the engineering properties of materials that will be incorporated in a structure is also required to adequately design the structure. Designers also need cost data related to the proposed construction product or technique to perform a cost comparison with other similar alternatives. One of the lessons learned with the use of EPS-block geofoam on the CA/T Project in Boston is the need to include a detailed numerical design example to complement design guidelines.

Therefore, the five primary research products required to ensure successful technology transfer of EPS-block geofoam technology to slope stability applications in new and existing roadway projects that are included in the project report are (1) summary of relevant engineering properties; (2) a comprehensive and usable design guideline; (3) a material, product, and construction standard; (4) economic data; and (5) a detailed numerical example. In addition to these five primary research products, an overview of construction tasks that are frequently encountered during EPS-block geofoam slope projects and four case histories that provide examples of cost-effective and successful EPS-block geofoam slope stabilization projects completed in the United States are included in the project report.

These key research products facilitate the accomplishment of the overall research objective of this study, which is to develop a comprehensive document that provides design guidance to engineers, owners, and regulators for the use of EPS-block geofoam for the function of lightweight fill in slope stability applications.

NCHRP PROJECT 24-11(02) FINAL REPORT

The contractor's final report for NCHRP Project 24-11(02) can be accessed via TRB.org/NCHRP by linking to the project page. The following are the report's contents:

- Chapter 1—overview of EPS-block geofoam, a summary of the NCHRP 24-11(01) study, problem statement of the current project, and the research objective.
- Chapter 2—summary of the research approach.
- Chapter 3—overview of EPS block engineering properties most relevant to the design of slopes stabilized with EPS blocks.
- Chapter 4—design methodology developed herein for slopes incorporating EPS-block geofoam for the function of lightweight fill in slope stability stabilization and repair.
- Chapter 5—overview of construction tasks frequently encountered during EPS-block geofoam slope projects.
- Chapter 6—background for understanding the recommended EPS-block geofoam standard for slope stability applications included in Appendix F.
- Chapter 7—summary of case histories that successfully incorporated EPS-block geofoam in slope stabilization applications.
- Chapter 8—cost information/cost estimate for geofoam slope stabilization for the design phase.
- Chapter 9—conclusions, recommendations, and of future research.
- Appendix A—geofoam usage survey and its responses.
- Appendix B—recommended design guideline for EPS-block geofoam slopes.
- Appendix C—two procedures developed for optimizing the volume and location of EPS blocks within the slope: one for landslides involving rotational slides, and one for translational slides.
- Appendix D—results of the study performed to determine the impact of typical centrifugal loads on an EPS-block fill mass.
- Appendix E—design example demonstrating the design methodology included in Chapter 4 and outlined in the design guideline included in Appendix B.
- Appendix F—recommended standard for use of EPS-block geofoam, which should facilitate DOTs in specifying and contracting for the use of geofoam in slope stabilization and repair projects.
- Appendixes G and H—example design details and example slope stabilization specifications.
- Appendix I—draft of a contract special provision for price adjustment for EPS-block geofoam to minimize the impact of short-term oil price fluctuations on the cost of EPS-block geofoam during multi-phased projects.
- Appendixes J and K—Phase I and II work plans.
- Appendix L—bibliography.

HOW TO USE THIS DIGEST

This digest provides a general overview of the following key project research products that are included in the project report: summary of engineering properties of block-molded EPS relevant to slope stabilization, general overview of the design guideline for the use of EPS blocks for slope stabilization and repair, an introduction to construction practices frequently encountered during EPS-block geofoam slope projects, an overview of the recommended EPS-block geofoam standard for slope stability applications, and a summary of the economic analysis related to EPS-block geofoam.

The intent of this digest is only to promote early awareness of the project results in order to encourage implementation. This digest is not intended to be used as a stand-alone document, so readers should review the project report before implementing any information included in this digest.

ENGINEERING PROPERTIES OF BLOCK-MOLDED EPS RELEVANT TO SLOPE STABILIZATION

The relevant engineering properties of block-molded EPS for the application of lightweight fill include physical, mechanical (stress-strain-time-temperature), and thermal. A comprehensive overview of these engineering properties of EPS is included in *NCHRP Web Document 65* (Stark et al.

2004b). Additionally, the primary elements of the molding process are included in *NCHRP Web Document 65* because the EPS-block molding process can influence the quality and other performance aspects of EPS-block geofoam to include the physical, mechanical, and thermal properties. Within the web document, Chapter 3 provides an overview of EPS-block engineering properties that are most relevant to the design of slopes stabilized with EPS blocks. These properties include shear strength and density. Because limit equilibrium methods of slope stability analysis are commonly used for analyzing slopes, an overview of the various approaches available to model the strength of the EPS blocks in limit equilibrium procedures of slope stability analysis is also presented in Chapter 3.

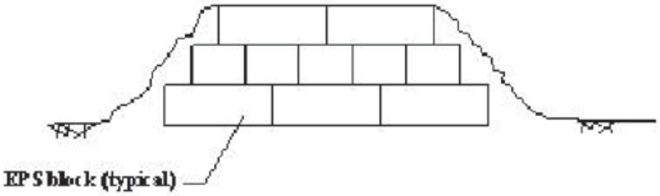
Interface friction, primarily along horizontal surfaces, is an important consideration in external and internal stability assessments under horizontal loads such as in slopes and seismic shaking. Tables 3.1 and 3.2, which are included in Chapter 3 in the web document, provide a summary of interface shear strength data for EPS/EPS interfaces and EPS/dissimilar material interfaces, respectively, which are the two types of interfaces that are of interest for EPS-block geofoam in lightweight fill applications.

If the calculated shear resistance along the horizontal planes between EPS blocks are insufficient to resist the horizontal driving forces, additional resistance between EPS blocks is generally provided by adding interblock mechanical connectors along the horizontal interfaces between the EPS blocks or the use of shear keys. The use of polyurethane adhesives, which are used for roofing applications, could be effective in providing additional shear resistance between EPS blocks in the future once long-term durability testing indicating that the shear strength provided by adhesives will not degrade with time is available.

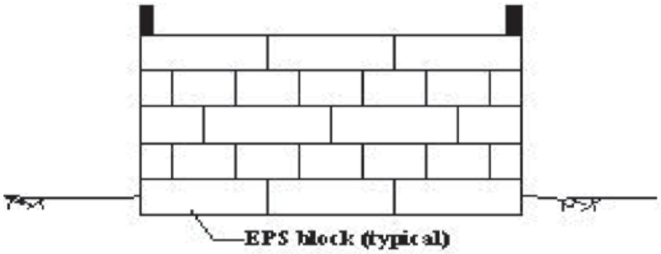
DESIGN METHODOLOGY

Introduction

The recommended design guideline included in *NCHRP Report 529* and *NCHRP Web Document 65* (Stark et al. 2004a; Stark et al. 2004b) is limited to stand-alone embankments that have a transverse (cross-sectional) geometry such that the two sides are more or less of equal height as shown conceptually in Figure 1. Slope stability applications (sometimes referred to as "side-hill fills") are shown in Figure 2. As shown in Figure 2, the use of EPS-block geofoam in slope applications can involve a slope-sided fill [Figure 2 (a)] or a vertical-sided fill [Figure 2 (b)]. The latter application is sometimes referred to as a "geofoam wall," and this application is unique to EPS-block geofoam. The use of a vertical-sided fill will minimize the amount of right-of-way needed and will also minimize the impact of fill loads on nearby structures. For vertical-sided

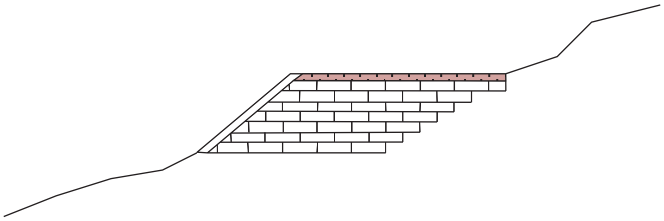


(a) Slope-sided fill.

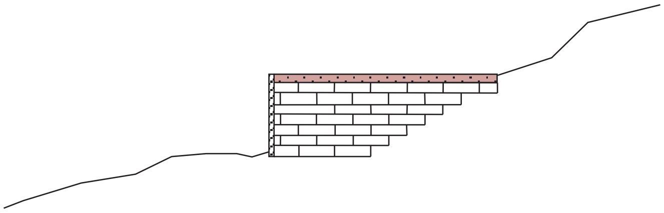


(b) Vertical-sided fill (Geofoam wall).

Figure 1. Typical EPS-block geofoam applications involving stand-alone embankments (Horvath 1995; Stark et al. 2004a).



(a) Slope-sided fill.



(b) Vertical-sided fill (Geofoam wall).

Figure 2. Typical EPS-block geofoam applications involving side-hill fills.

embankment walls, the exposed sides should be covered with a facing. The facing does not have to provide any structural capacity to retain the blocks because the blocks are self-stable, so the primary function of the facing is to protect the blocks from environmental factors.

The recommended design procedure for the use of EPS-block geofoam for slope stabilization and repair is presented by initially introducing the major components of an EPS-block geofoam slope system and the three primary failure modes—that is, external instability, internal instability, and pavement system failure—which need to be considered during design. An overview of the recommended design procedure is then provided.

Major Components of an EPS-Block Geofoam Slope System

Figure 3 shows that an EPS-block geofoam slope system consists of three major components:

- The **existing slope material,** which can be divided into the upper and lower slope. Also, the slope material directly below the fill mass is also referred to as the foundation material;
- The proposed **fill mass,** which primarily consists of EPS-block geofoam. In addition, depending on whether the fill mass has sloped (slope-sided fill) or vertical (vertical-sided fill) sides, there is either soil or a protective structural cover over the sides of the EPS blocks; and
- The proposed **pavement system,** which is defined as including all material layers, bound and unbound, placed above the EPS blocks.

Failure Modes

Overview. Potential failure modes that must be considered during stability evaluation of an EPS-block geofoam slope system can be categorized into the same two general failure modes that a designer must consider in the design of soil nail walls (Lazarte et al. 2003) and mechanically stabilized earth walls (Elias et al. 2001). These failure modes are external and internal failure modes. EPS-block geofoam slope systems may also incorporate a pavement system, so to design against failure, the overall design process includes the evaluation of these three failure modes and must include the following design considerations:

- Design for **external stability** of the overall EPS-block geofoam slope system configuration;
- Design for **internal stability** of the fill mass; and
- Design of an appropriate **pavement system** for the subgrade provided by the underlying EPS blocks.

Table 1 provides a summary of the three failure modes and the various failure mechanisms that need to be considered for each failure mode. Each failure mechanism has also been categorized into either an ultimate limit state (ULS) or serviceability limit state (SLS) failure. The failure mechanisms are conceptually similar to those considered in the design of stand-alone EPS-block geofoam embankments over soft ground (Stark et al. 2004a; Stark et al. 2004b) as well as those that are considered in the design of soil nail walls (Lazarte et al. 2003) and other types of geosynthetic structures used in road construction—for example, mechanically stabilized earth walls (MSEWs) and reinforced soil slopes (RSS) (Elias et al. 2001). Additionally, some of the failure

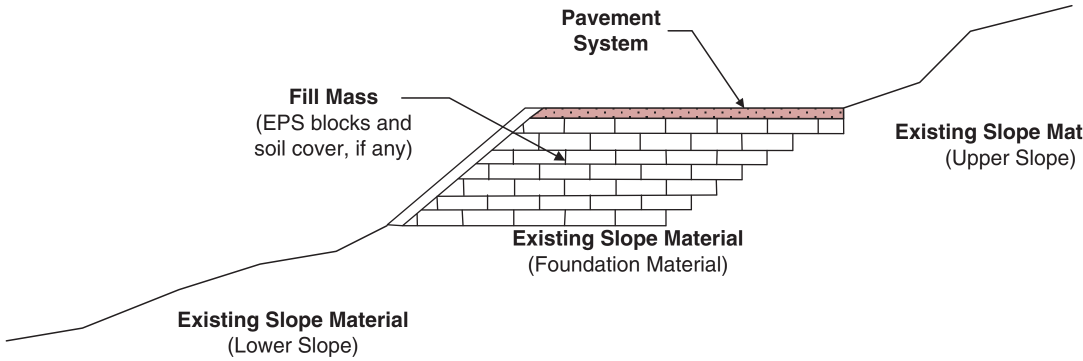


Figure 3. Major components of an EPS-block geofoam slope system.

Table 1. Summary of failure modes and mechanisms incorporated in the proposed design procedure for EPS-block geofoam as a lightweight fill in slope stability application.

Failure Mode	Limit State	Failure Mechanism	Accounts for
External Instability	ULS	Static slope stability	Global stability involving a deep-seated slip surface and slip surfaces involving the existing slope material only (Figure 4). Also considers slip surfaces that involve both the fill mass and existing slope material (Figure 5).
	ULS	Seismic slope stability	Same as for static slope stability but considers seismic-induced loads.
	SLS	Seismic settlement	Earthquake-induced settlement due to compression of the existing foundation material (Figure 9) such as those resulting from liquefaction, seismic-induced slope movement, regional tectonic surface effects, foundation soil compression due to cyclic soil densification, and increase due to dynamic loads caused by rocking of the fill mass (Day 2002).
	ULS	Seismic bearing capacity	Bearing capacity failure of the existing foundation earth material (Figure 8) due to seismic loading and, potentially, a decrease in the shear strength of the foundation material.
	ULS	Seismic sliding	Sliding of the entire EPS-block geofoam fill mass (Figure 6) due to seismic-induced loads.
	ULS	Seismic overturning	Overturning of the entire embankment at the interface between the bottom of the assemblage of EPS blocks and the underlying foundation material as a result of seismic forces (Figure 7).
	SLS	Settlement	Excessive and/or differential settlement from vertical and lateral deformations of the underlying foundation soil (Figure 9).
	ULS	Bearing capacity	Bearing capacity failure of the existing foundation earth material (Figure 8) resulting in downward vertical movement of the entire fill mass into the foundation soil.
Internal Instability	ULS	Seismic sliding	Horizontal sliding between layers of blocks and/or between the pavement system and the upper layer of blocks (Figure 10) due to seismic-induced loads.
	SLS	Seismic load bearing	Excessive vertical deformation of EPS blocks due to increase in the vertical normal stress within the EPS-block fill mass due to the moment produced by the seismic-induced inertia force.
	SLS	Load bearing	Excessive vertical deformation of EPS blocks (Figure 11) due to excessive initial (immediate) deformations under dead or gravity loads from the overlying pavement system, excessive long-term (for the design pavement system, excessive long-term (for the design life of the fill) creep deformations under the same gravity loads, and/or excessive non-elastic or irreversible deformations under repetitive traffic loads.
Pavement System Failure	SLS	Flexible or rigid pavement	Premature failure of the pavement system (Figure 12), as well as to minimize the potential for differential icing (a potential safety hazard). Providing sufficient support, either by direct embedment or structural anchorage, for any road hardware (guardrails, barriers, median dividers, lighting, signage and utilities).

SLS=serviceability limit state
ULS=ultimate limit state

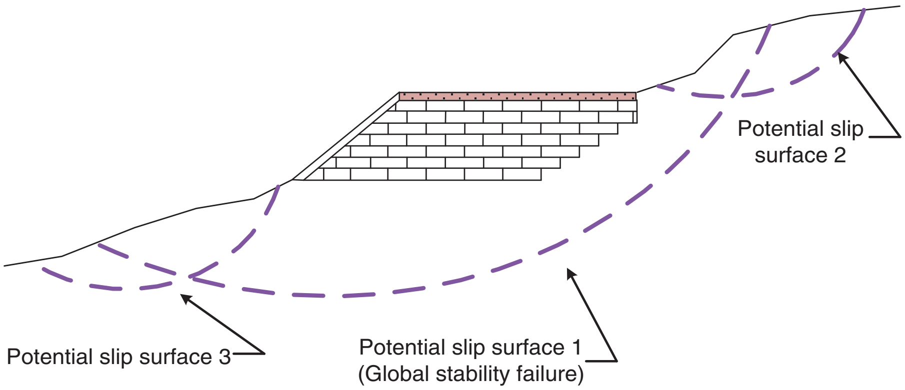


Figure 4. Static and seismic slope stability involving existing soil slope material only.

mechanisms shown in Table 1 are also included in the Japanese design procedure that Tsukamoto (1996) provides. The three failure modes are subsequently described in more detail.

External Instability Failure Mode. Design for external stability of the overall EPS-block geofoam slope system considers failure mechanisms that involve the existing slope material only as shown in Figure 4 as well as failure mechanisms that involve both the fill mass and the existing slope material as shown in Figure 5. The latter potential failure surface is similar to the "mixed" failure mechanism identified by Byrne et al. (1998) for soil nailed walls, whereby the failure surface intersects soil outside the soil nail zone as well as some of the soil nails. The evaluation of the external stability failure mechanisms includes consideration of how the combined fill mass and overlying pavement system interacts with the existing slope material. The external stability failure mechanisms included in the NCHRP Project 24-11(01) design procedure for stand-alone EPS-block geofoam embankments consisted of bearing capacity of the foundation material, static and seismic slope stability, hydrostatic uplift (flotation), translation and overturning due to water (hydrostatic sliding), translation and overturning due to wind, and settlement.

The Japanese design procedure specifically considers the hydrostatic uplift failure mechanism (Tsukamoto 1996). Many of the EPS-block geofoam slope case histories evaluated as part of this NCHRP project include the use of underdrain systems below the EPS blocks to prevent water from accumulating above the bottom of the EPS blocks and, in some cases, incorporate a drainage system between the adjacent upper slope material and the EPS blocks to collect and divert seepage water, thereby alleviating seepage pressures. Thus, based on current design precedent, it is recommended that all EPS-block geofoam slope systems incorporate drainage systems. If a drainage system that will

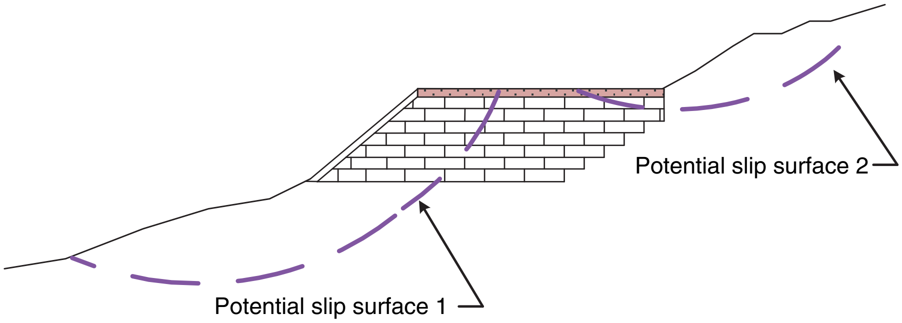


Figure 5. Static and seismic slope stability involving both the fill mass and existing soil slope material.

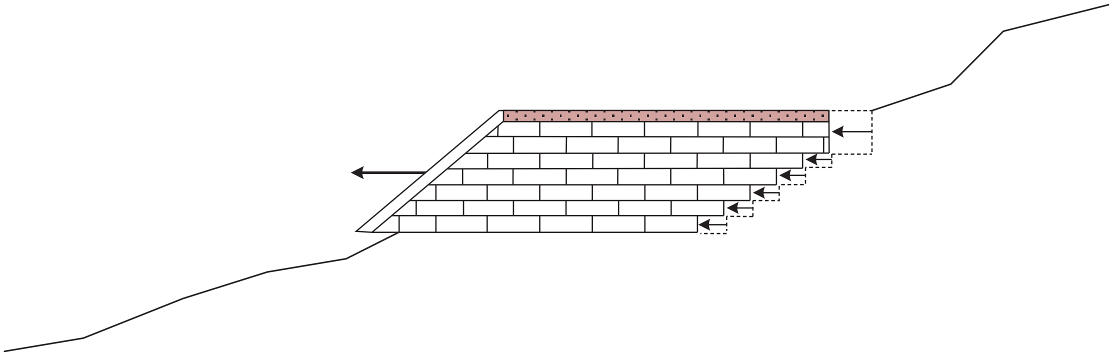


Figure 6. External seismic stability failure involving horizontal sliding of the entire embankment.

ensure that water from seepage or surface runoff will not accumulate at or above the bottom of the EPS blocks is part of the design, then analyses for the hydrostatic uplift (flotation) and translation due to water failure mechanisms that are included in the NCHRP Project 24-11(01) design procedure for stand-alone EPS-block embankments are not required in slope applications. The final drainage system configuration should maintain positive drainage throughout the slope, so the hydrostatic uplift and translation due to water failure mechanisms are not included in the current recommended design procedure for slope applications. It should be noted that in addition to a permanent drainage system, temporary dewatering and drainage systems need to be considered during construction.

Translation and overturning due to wind is a failure mechanism that is considered in the NCHRP Project 24-11(01) design of stand-alone embankments incorporating EPS blocks. Wind loading is not considered in the Japanese recommended design procedure for the use of EPS blocks in slopes (Tsukamoto 1996). In stand-alone embankments, the primary concern with wind loading is horizontal sliding of the blocks; however, in slope applications, the EPS blocks will typically be horizontally confined by the existing slope material on one side of the slope as shown in Figure 2. Thus, wind loading does not appear to be a potential failure mechanism for EPS-block geofoam slopes, so the wind loading failure mechanism is not included in the current recommended design procedure. However, it is recommended that additional research be performed based on available wind pressure results on structures located on the sides of slopes to further evaluate the need to consider wind as a potential failure mechanism.

Potential failure mechanisms associated with external instability due to seismic loads include slope instability involving slip surfaces through the existing slope material only (as shown in Figure 4) and/or both the fill mass and the existing slope material (as shown in Figure 5); horizontal sliding of the entire EPS-block geofoam fill mass (as shown by Figure 6); overturning of a vertical-sided embankment (as shown by Figure 7); bearing capacity failure of the existing foundation earth

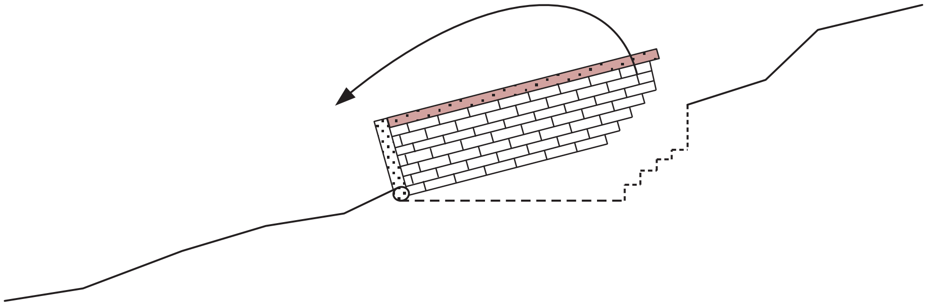


Figure 7. External seismic stability failure involving overturning of an entire vertical embankment about the toe of the embankment.

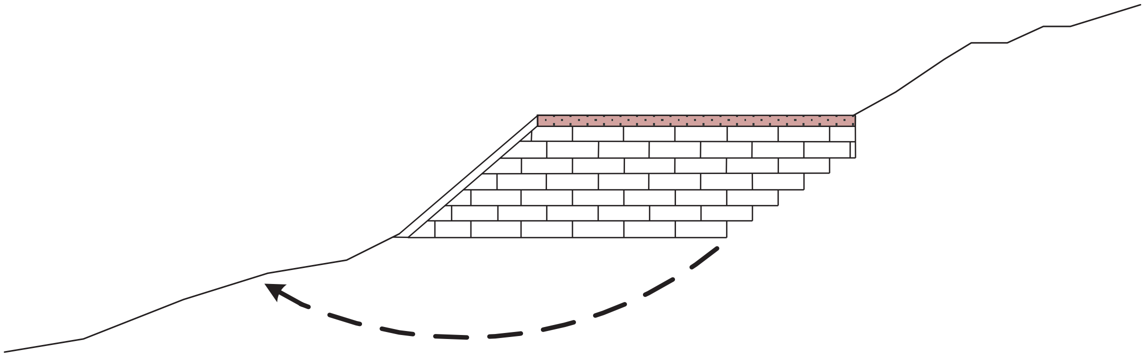


Figure 8. Bearing capacity failure of the embankment due to general shear failure or local shear failure.

material due to static loads and seismic loads and/or a decrease in the shear strength of the foundation material (as shown in Figure 8); and earthquake-induced settlement of the existing foundation material (as shown by Figure 9).

In summary, Table 1 shows the external stability failure mechanisms that are included in the proposed design procedure consist of static slope stability, settlement, and bearing capacity. Additional failure mechanisms associated with external seismic stability include seismic slope instability, seismic-induced settlement, seismic bearing capacity failure, seismic sliding, and seismic overturning. These failure considerations together with other project-specific design inputs such as right-of-way constraints, limiting impact on underlying and/or adjacent structures, and construction time usually govern the overall cross-sectional geometry of the fill. Because EPS-block geofoam is typically a more-expensive material than soil on a cost-per-unit-volume basis for the material alone, it is desirable to minimize the volume of EPS used yet still satisfy external instability design criteria concerning settlement, bearing capacity, static slope stability, and the various seismic-related failure mechanisms.

Internal Instability Failure Mode. Design for internal stability considers failure mechanisms within the EPS-block geofoam fill mass. The internal instability failure mechanisms included in the NCHRP Project 24-11(01) design procedure for stand-alone embankments consists of translation due to water and wind, seismic stability, and load bearing. As previously indicated in the external instability failure mode discussion, translation due to water and wind does not appear to be applicable to EPS-block geofoam slope systems. The translation due to water failure mechanism is not applicable provided that a drainage system will ensure water from seepage or surface runoff will not accumulate at or above the bottom of the EPS blocks. Therefore, seismic stability, which consists of seismic horizontal sliding and seismic load bearing of the EPS blocks, and load bearing of the EPS blocks appear to be the primary internal instability failure mechanisms that need to be considered in EPS-block slope systems.

Static slope stability is not an internal stability failure mechanism for stand-alone embankments and is not part of the internal stability design phase in the NCHRP Project 24-11(01) design procedure for stand-alone embankments because there is little or no static

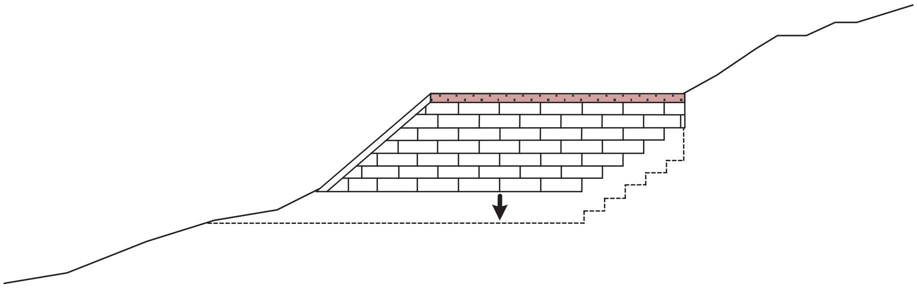


Figure 9. Excessive settlement.

driving force within the EPS-block fill mass causing instability. The driving force is small because the horizontal portion of the internal failure surfaces is assumed to be along the EPS-block horizontal joints and completely horizontal while the typical static loads are vertical. The fact that embankments with vertical sides can be constructed demonstrates the validity of this conclusion.

For geofoam slope applications, the potential of the EPS-block fill mass to withstand earth pressure loads from the adjacent upper slope material as depicted in Figure 3 was evaluated as part of this study. Horizontal sliding between blocks and/or between the pavement system and the upper level of blocks due to adjacent earth pressures is a failure mechanism that needs to be considered if the adjacent slope is not self-stable. Since the mass of the EPS-block fill is typically very small, it may not be feasible for the EPS fill to directly resist external applied earth forces from the adjacent slope material. Because the interface shear resistance of EPS/EPS interfaces is related to the normal stress, which is primarily due to the mass of the EPS blocks, the shear resistance between blocks may not be adequate to sustain adjacent earth pressures. Therefore, the design procedure is based on a self-stable adjacent upper slope to prevent earth pressures on the EPS fill mass that can result in horizontal sliding between blocks. Although the design procedure is based on a self-stable adjacent slope, it may be possible to utilize an earth-retention system in conjunction with an EPS-block geofoam slope system to support a portion of the upper adjacent slope.

The primary evaluation of internal seismic stability involves determining whether the geofoam embankment will behave as a single, coherent mass when subjected to seismic loads. Because EPS blocks consist of individual blocks, the collection of blocks will behave as a coherent mass if the individual EPS blocks exhibit adequate vertical and horizontal interlock. The standard practice of placing blocks such that the vertical joints between horizontal layers of EPS blocks are offset should provide adequate interlocking in the vertical direction. Therefore, the primary seismic internal stability issue is the potential for horizontal sliding along the horizontal interfaces between blocks and/or between the pavement system and the upper layer of blocks as shown by Figure 10.

Load-bearing failure of the EPS blocks due to excessive dead or gravity loads from the overlying pavement system and traffic loads is the third internal stability failure mechanism. The primary consideration during load bearing analysis is the proper selection and specification of EPS properties so the geofoam mass can support the overlying pavement system and traffic loads without excessive immediate and time-dependent (creep) compression that can lead to excessive settlement of the pavement surface (an SLS consideration) as shown in Figure 11. The load-bearing analysis procedure for stand-alone embankments (Arellano and Stark 2009a; Stark et al. 2004a; Stark et al. 2004b) is also included in the design procedure for slope applications.

In summary, Table 1 shows the three internal instability failure mechanisms that are evaluated in the design guideline are seismic horizontal sliding, seismic load bearing of the EPS blocks, and static load bearing of the EPS blocks.

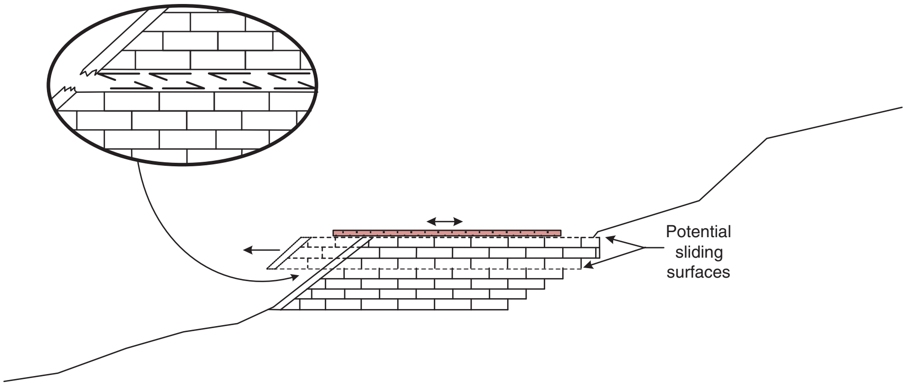


Figure 10. Internal seismic stability failure involving horizontal sliding between blocks and/or between the pavement system and the upper layer of blocks due to seismic loading.

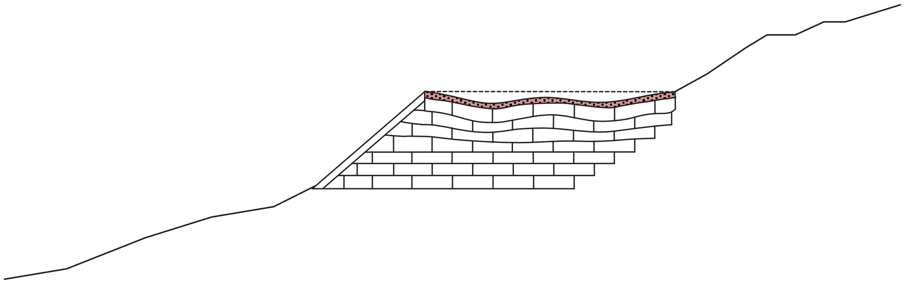


Figure 11. Load bearing failure of the blocks involving excessive vertical deformation.

Pavement System Failure Mode. The objective of pavement system design is to select the most economical arrangement and thickness of pavement materials for the subgrade provided by the underlying EPS blocks. The design criterion is to prevent premature failure of the pavement system such as rutting, cracking, or similar criterion, which is an SLS-type of failure (Figure 12) as well as to minimize the potential for differential icing (a potential safety hazard) and solar heating (which can lead to premature pavement failure) in those areas where climatic conditions make these potential problems. Also, when designing the pavement cross-section overall, consideration must be given to providing sufficient support, either by direct embedment or by structural anchorage, for any road hardware (i.e., guardrails, barriers, median dividers, lighting, signage, and utilities).

In summary, the three failure modes that must be considered during stability evaluation of an EPS-block geofoam slope system include external instability, internal instability, and pavement system failure. Table 1 provides a summary of the failure mechanisms that are evaluated for each failure mode as well as a summary of the limit state that is considered. The external instability failure mechanisms that are included in the proposed design procedure consist of static slope stability, settlement, and bearing capacity. Additional failure mechanisms associated with external seismic stability include seismic slope instability, seismic-induced settlement, seismic bearing capacity failure, seismic sliding, and seismic overturning. The three internal instability failure mechanisms that are evaluated in the design guideline are seismic horizontal sliding, seismic load bearing of the EPS blocks, and static load bearing of the EPS blocks. The design procedure that is presented below provides the recommended sequence for evaluating each of the failure mechanisms shown in Table 1.

Overview of Design Procedure

Figure 13 shows the recommended design procedure for EPS-block geofoam slope fills. (Procedures to analyze each step in Figure 13 are included in the NCHRP Project 24-11(02) final report, available via TRB.org/NCHRP by linking to the project page.) The design requirements of EPS-block geofoam slope systems are dependent on the location of the existing or anticipated slip surface in relation to the location of the existing or proposed roadway—that is, slide mass located above the roadway as shown in Figure 14 (a) or slide mass located below

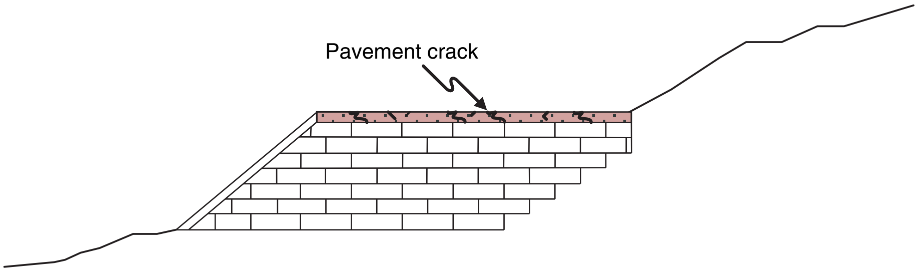


Figure 12. Pavement failure due to cracking.

Figure 13. Steps in the design procedure for EPS-block geofoam slope fills.

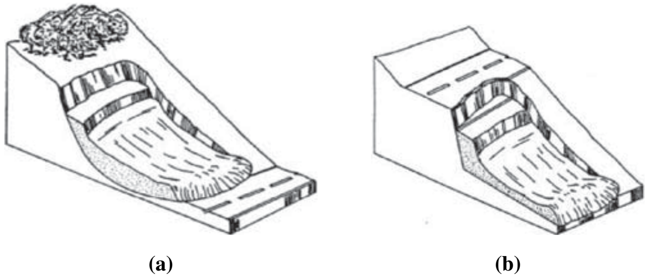


Figure 14. Location of slide mass relative to roadway: (a) slide above roadway and (b) slide below roadway. (Hopkins et al. 1988).

the roadway as shown in Figure 14 (b). All steps are required if the existing or proposed roadway is located *within* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *below* the roadway as shown in Figure 14 (b)—that is, the roadway is near the head of the slide mass.

If the existing or proposed roadway is located *outside* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *above* the roadway as shown in Figure 14 (a)—that is, the roadway is near the toe of the slide mass—the design procedure does not include Steps 8 and 9, which are directly related to the design of the pavement system, because the EPS-block geofoam slope system may not include a pavement system. It is anticipated that EPS-block geofoam used for this slope application will not support any structural loads other than possibly soil fill above the blocks. Therefore, only failure mechanisms associated with the external and internal instability failure modes, as shown in Table 1, are included in the modified design procedure shown in Figure 13 if the existing or proposed roadway is located *outside* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *above* the roadway. The pavement system failure mode may not be an applicable failure mode because if the roadway is near the toe of the slide mass, stabilization of the slide mass with EPS-block geofoam will occur primarily at the head of the slide and, consequently, the EPS-block geofoam slope system may not include the pavement system. Therefore, Steps 8 and 9 of the full design procedure shown in Figure 13, which involves the pavement system, may not be required and are not part of the modified design procedure shown in Figure 13 if the roadway is near the toe of the slide mass.

In summary, the full design procedure, which is applicable if the existing or proposed roadway is located *within* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *below* the roadway, as shown in Figure 14 (b), consists of all the design steps. If the existing or proposed roadway is located *outside* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *above* the roadway as shown in Figure 14 (a), the design procedure does not include Steps 8 and 9, which are directly related to the design of the pavement system, because the EPS-block geofoam slope system may not include a pavement system. Steps 8 and 9, which are associated with the pavement system, are shaded in Figure 13 to help differentiate between the complete design procedure that includes Steps 8 and 9 and the modified procedure shown that does not include Steps 8 and 9.

Figure 14 (a) does not imply that EPS blocks can be placed near the toe of the slide where removal of existing material and replacement with EPS blocks would contradict the function of lightweight fill, which is to decrease driving forces that contribute to slope instability, and would instead contribute to further instability. Therefore, Step 4 (static slope stability) must be performed to ensure that the proposed location of the EPS blocks will decrease driving forces and contribute to overall stability. The stabilization of a slide above a roadway scenario as shown in Figure 14 (a) is an alternative in which the use of EPS blocks would still be the greatest benefit near the crest of the slope above the roadway.

Figure 15 shows a design selection diagram that can be used to determine whether to use the complete procedure shown in Figure 13 or the modified design procedure without Steps 8 and 9 shown in Figure 13. In Figure 15, Level I of the decision diagram indicates that the proposed design procedure is applicable to both remedial repair and remediation of existing unstable soil slopes involving existing roadways as well as for design of planned slopes involving new roadway construction. Level II of the decision diagram indicates that for existing roadways, the use of EPS-block geofoam will typically only involve unstable slopes, but for new roadway construction, the use of EPS-block geofoam may involve an existing unstable slope or an existing stable slope that may become unstable during or after construction of the new roadway. Level III categorizes the location of the existing or anticipated slide mass location in relation

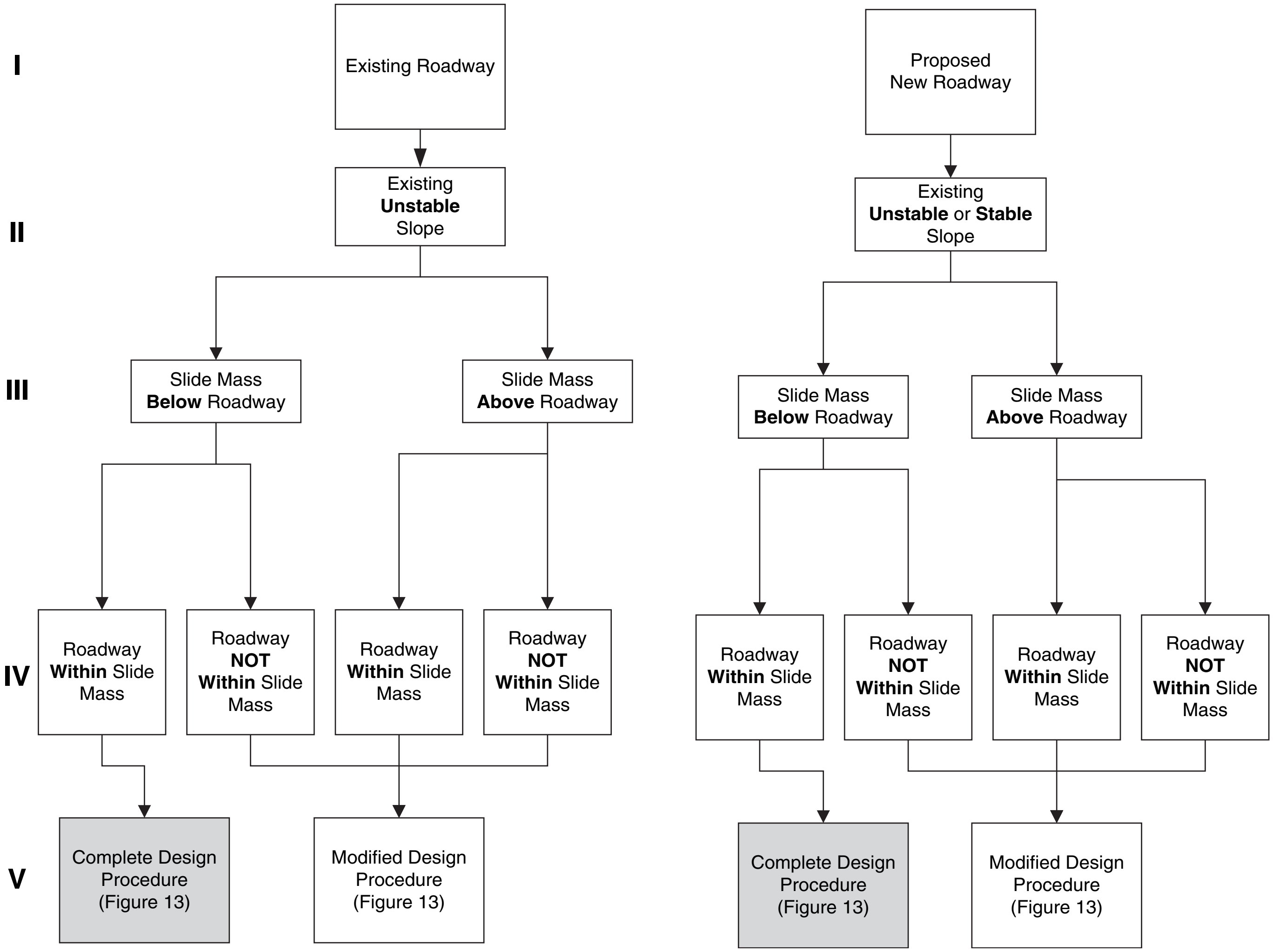


Figure 15. Design procedure selection diagram.

to the existing or proposed new roadway. Level IV indicates the location of the roadway in relation to the existing or anticipated slide mass.

Level V indicates the recommended design procedure that can be used for design. As shown in Figure 15, the complete design procedure shown in Figure 13 is applicable if the existing or proposed roadway is located within the existing or anticipated slide mass ***and*** the existing or anticipated slide mass is located below the roadway as shown in Figures 14(b)—that is, the roadway is near the head of the slide mass. The modified design procedure without Steps 8 and 9 shown in Figure 13 is applicable if the existing or proposed roadway is located outside the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located above the roadway as shown in Figures 14 (a)—that is, the roadway is near the toe of the slide mass.

One challenge of slope stabilization design with lightweight fill is to determine the volume and location of EPS blocks within the slope that will yield the required level of stability or factor of safety at the least cost. Because EPS-block geofoam is typically more expensive than soil on a cost-per-unit-volume basis for the material alone, it is desirable to optimize the volume of EPS used yet still satisfy design criteria concerning stability. Therefore, to achieve the most cost-effective design, a design goal for most projects is to use the minimum amount of EPS blocks possible that will satisfy the requirements for external and internal stability, so Steps 3 and 4 of the Figure 13 design procedure specifically include the optimization of the volume and location of the EPS blocks within the slope.

The determination of optimal volume and location of EPS blocks will typically require iterative analysis based on various locations and thicknesses until a cross section that yields the minimum volume of lightweight fill at the desired level of stability is obtained. However, other factors will also impact the final design volume and location of EPS blocks such as

- Construction equipment access to perform excavation work,
- Ease of accessibility for EPS-block delivery and placement,
- Impact on traffic if lightweight fill will be incorporated below an existing roadway, and
- Right-of-way constraints and/or constraints due to nearby structures.

It should be noted that although minimization of EPS volume is the goal on most projects, for some projects it may be desirable to maximize the use of EPS. For example, economization of EPS volume may not be a concern in some emergency slope repair projects or projects with an accelerated construction schedule.

The preliminary width and location of the EPS-block geofoam fill mass within the slope will be dependent on the results of the evaluation of the preliminary geometric requirements of the proposed EPS-block fill mass performed as part of Step 1. The most effective location of the lightweight fill mass will be near the head (upper portion) of the existing slide mass or proposed slope because reducing the load at the head by removing existing earth material and replacing it with a lighter fill material will contribute the most to reducing the destabilizing forces that tend to cause slope instability. The location of the fill mass within the slope selected in Step 1 is only preliminary because the location of the fill mass as well as the thickness may change as various iterations of the fill mass arrangement are evaluated to obtain a fill mass arrangement that will satisfy the design criteria of the various failure mechanisms that are analyzed in each supplemental design step shown in Figure 13.

In some projects, the volume and location of EPS blocks within the slope will be constrained by the previously indicated factors. For example, for the case of the existing road that is located within the existing slide mass and the existing slide mass that is located below the roadway as shown in Figure 14 (b)—that is, the roadway is near the head of the slide mass—the location of the EPS fill mass will typically be limited within the existing roadway location because of right-of-way constraints. However, in some projects the volume and location of EPS within the slope may not be obvious and may require that various iterations of the fill mass arrangement be evaluated to obtain a fill mass arrangement that will satisfy the design requirements of the various failure mechanisms that are analyzed in each design step shown in Figure 13. Therefore, as part of this project, a study was performed to develop a procedure for optimizing the volume and location of EPS blocks within the slope to minimize the number of iterations that may be required to satisfy the design criterion.

In the NCHRP Project 24-11 (02) final report, Appendix C presents two procedures for optimizing the volume and location of EPS blocks within the slope. One procedure is for slides involving rotational slip surfaces, and the other for translational slides. The purpose of the optimization methods is only to obtain an approximate location within the slope where the placement of EPS blocks will have the greatest impact in stabilizing the slope while requiring the minimum volume of EPS blocks. A separate static slope stability analysis must be performed as part of Step 5 of the design procedure as shown in Figure 13 with a better slope stability analysis method that preferably satisfies full equilibrium such as Spencer's method. Step 5 is what should be relied on to verify that the overall slope configuration meets the desired factor of safety.

The design procedure is based on a self-stable adjacent upper slope to prevent earth pressures on the EPS fill mass that can result in horizontal sliding between blocks. If the adjacent slope material cannot be cut to a long-term stable slope angle, an earth-retention system must be used in conjunction with the ESP fill mass to resist the applied earth force.

Many of the EPS-block geofoam slope case histories evaluated as part of this research included the use of underdrain systems below the EPS blocks to prevent water from accumulating above the bottom of the EPS blocks and, in some cases, incorporated a drainage system between the adjacent upper slope material and the EPS blocks to collect and divert seepage water, thereby alleviating seepage pressures. Thus, based on current design precedent, it is recommended that all EPS-block geofoam slope systems incorporate drainage systems. It should be noted that in addition to a permanent drainage system, temporary dewatering and drainage systems need to be considered during construction.

In addition to the technical aspects of the design, cost must also be considered. Because EPS-block geofoam is typically a more expensive material than soil on a cost-per-unit-volume basis for the material alone, it is desirable to optimize the design to minimize the volume of EPS used yet still satisfy the technical design aspects of the various failure mechanisms. It is possible in concept to optimize the final design of both the pavement system and the overall EPS-block slope system considering both performance and cost so that a technically effective and cost-efficient geofoam slope system is obtained. However, because of the inherent interaction among the three major components of a geofoam slope system shown in Figure 3, overall design optimization of a slope incorporating EPS-block geofoam requires iterative analyses to achieve a technically acceptable design at the lowest overall cost. In order to minimize the iterative analysis, the design algorithm shown in Figure 13 was developed. The design procedure depicted in this figure considers a pavement system with the minimum required thickness, a fill mass with the minimum thickness of EPS-block geofoam, and the use of an EPS block with the lowest possible density. Therefore, the design procedure shown in Figure 13 will produce a cost-efficient design.

Summary

As shown in Figure 3, the design of an EPS-block geofoam slope system considers the interaction of three major components: existing slope material, the fill mass, and the pavement system. The three potential failure modes that can occur due to the interaction of these three primary components of an EPS slope system and that must be considered during stability evaluation of an EPS-block geofoam slope system include external instability of the overall EPS-block geofoam slope system configuration, internal instability of the fill mass, and pavement system failure.

Design for external stability of the overall EPS-block geofoam slope system considers failure mechanisms that involve the existing slope material only, as shown in Figure 4, as well as failure mechanisms that involve both the fill mass and the existing slope material, as shown in Figure 5. The external instability failure mechanisms that are included in the proposed design procedure consist of static slope instability, settlement, and bearing capacity. Additional failure mechanisms associated with external seismic stability include seismic slope instability, seismic-induced settlement, seismic bearing capacity failure, seismic sliding, and seismic overturning.

Design for internal stability considers failure mechanisms within the EPS-block geofoam fill mass. The three internal instability failure mechanisms that are evaluated in the design guideline are seismic horizontal sliding, seismic load bearing of the EPS blocks, and static load bearing of the EPS blocks.

The objective of pavement system design is to select the most economical arrangement and thickness of pavement materials for the subgrade provided by the underlying EPS blocks. The design criteria are to prevent premature failure of the pavement system as well as to minimize the potential for differential icing (a potential safety hazard) and solar heating (which can lead to premature pavement failure) in those areas where climatic conditions make these potential problems. Also, when designing the pavement cross section overall, consideration must be given to providing sufficient support—either by direct embedment or structural anchorage—for any road hardware (i.e., guardrails, barriers, median dividers, lighting, signage, and utilities).

Figure 13 shows the recommended design procedure for EPS-block geofoam slope fills (procedures to analyze each step in Figure 13 are included in the NCHRP Project 24-11(02) final report). All steps are required if the existing or proposed roadway is located *within* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *below* the roadway as shown in Figure 14 (b). If the existing or proposed roadway is located *outside* the limits of the existing or anticipated slide mass ***and/or*** the existing or anticipated slide mass is located *above* the roadway as shown in Figure 14 (a), the design procedure does not include Steps 8 and 9, which are directly related to the design of the pavement system, because the EPS-block geofoam slope system may not include a pavement system.

For EPS blocks utilized in slope stabilization and repair that do not support a pavement system or heavy structural loads, the potential to utilize EPS blocks with recycled EPS exists. The use of recycled EPS blocks would be an attractive "green" product that reduces waste by recycling polystyrene scrap and would also reduce the raw materials costs in the production of EPS. Arellano et al. (2009b) have evaluated the mechanical properties of expanded recycled polystyrene aggregate and are currently evaluating the mechanical properties of EPS blocks that consist of recycled polystyrene beads.

The design of an EPS-block geofoam slope system requires consideration of the interaction among the three major components of an EPS-block slope system shown in Figure 3—that is, existing slope material, fill mass, and pavement system. Because of this interaction, the design procedure involves interconnected analyses among the three components. For example, some issues of pavement system design act opposite to some of the design issues involving external and internal stability of an EPS-block geofoam slope system because a robust pavement system is a benefit for the long-term durability of the pavement system, but the larger dead load from a thicker pavement system may decrease the factor of safety of the failure mechanisms involving external and internal stability of the geofoam slope system. Therefore, some compromise between failure mechanisms is required during design to obtain a technically acceptable design.

However, in addition to the technical aspects of the design, cost must also be considered. Because EPS-block geofoam is typically a more-expensive material than soil on a cost-per-unit-volume basis for the material alone, it is desirable to optimize the design to minimize the volume of EPS used yet still satisfy the technical design aspects of the various failure mechanisms. It is possible in concept to optimize the final design of both the pavement system and the overall EPS-block slope system considering both performance and cost so that a technically effective and cost-efficient geofoam slope system is obtained. However, because of the inherent interaction among components, overall design optimization of a slope incorporating EPS-block geofoam requires iterative analyses to achieve a technically acceptable design at the lowest overall cost. In order to minimize the iterative analysis, the design algorithm shown in Figure 13 was developed. The design procedure depicted in this figure considers a pavement system with the minimum required thickness, a fill mass with the minimum thickness of EPS-block geofoam, and the use of an EPS block with the lowest possible density. Therefore, the design procedure will produce a cost-efficient design.

Currently, no formal design guidelines to use any type of lightweight fill for slope stabilization by reducing the driving forces are available. Therefore, the proposed recommended design guideline that was developed herein for EPS-block geofoam can also serve as a blueprint for the use of other types of lightweight fills in slope stability applications.

An overview of the basis of the design procedure shown in Figure 13 was introduced in a presentation titled "A Framework for the Design Guideline for EPS-Block Geofoam in Slope Stabilization and Repair" at the 22nd Annual Meeting of the Tennessee Section of ASCE in 2009 and at the 89th Annual Meeting of the Transportation Research Board in January, 2010. The corresponding TRB paper was published in 2010 in *Transportation Research Record 2170* (Arellano et al. 2010). The design procedure shown on Figure 13 was also presented at the 4th International Conference on Geofoam Blocks in Construction Applications (EPS 2011 Norway) (Arellano et al., 2011).

The research has revealed important analysis and design differences between the use of EPS-block geofoam for the lightweight fill function in slope applications versus stand-alone applications over soft ground. The primary differences between slope applications versus stand-alone embankments over soft ground are summarized below:

- Site characterization is usually much more complex and difficult because it typically involves explorations made on an existing slope and concomitant access difficulties; the slope cross section often consists of multiple soil and rock layers that vary in geometry both parallel and perpendicular to the road alignment; and piezometric conditions may be very complex and even seasonal in variation.
- The governing design issue is usually based on a ULS failure involving the analysis of shear surfaces using material strength and limit-equilibrium techniques. SLS considerations involving material compressibility and global settlement of the fill are rarely a concern.
- There is always an unbalanced earth load, often relatively significant in magnitude, acting on the EPS mass that must be addressed as part of the design process.
- Piezometric conditions are often a significant factor to be addressed in design. In fact, if the use of EPS geofoam is being considered to reconstruct a failed or failing area, piezometric

issues typically contribute to the cause of the failure in the first place.
- The volume of EPS placed within the overall slope cross section may be relatively limited. Furthermore, the optimal location of the EPS mass within the overall slope cross section is not intuitively obvious.
- The road pavement may not overlie the portion of the slope where the EPS is placed, so load conditions on the EPS blocks may be such that blocks of relatively low density can be used, which can achieve economies in the overall design.

CONSTRUCTION PRACTICES

An overview of construction tasks that are frequently encountered during EPS-block geofoam slope projects is included in Chapter 5 of the NCHRP Project 24-11(02) final report. The construction topics included in Chapter 5 include site preparation; drainage; EPS-block shipment, handling, and storage; construction QA/construction QC of EPS blocks; block placement; backfill placement between EPS blocks and adjacent earth slopes; phased construction; accommodation of utilities and road hardware; facing wall; earth retention system; pavement construction; and post-construction monitoring.

Figures and photographs that may aid in preparation of bid and construction documents are included in Chapter 5. Additionally, Appendix G includes various design details and Appendix H includes example specifications utilized in geofoam projects. The construction details included in Appendix G, which were obtained from actual geofoam construction drawings used in projects throughout the United States, can be used as a guide for developing site-specific drawings or details. The details presented relate to a variety of geofoam issues such as configuration of the EPS blocks, inclusion of utilities and roadway hardware, construction of a load distribution slabs over the EPS, and construction of facing walls.

In addition to ensuring that the correct EPS-block-type is placed, it is also important to ensure that the methods being used by the contractor to construct the overall EPS-block geofoam slope produce an acceptable slope system that complies with the assumptions inherent in the recommended design procedure. For example, the design procedure assumes that the adjacent slope is self-stable to prevent earth loads from developing on the EPS-block fill mass and that an adequate drainage system is provided to prevent hydrostatic and seepage forces from developing within the EPS fill mass. Therefore, it is necessary to monitor the construction process to ensure that the adjacent slope is indeed stable and that the drainage system is constructed properly.

Lessons learned from four case histories are presented in Chapter 7 to provide examples of cost-effective and successful EPS-block geofoam slope stabilization projects completed in the United States. These case histories demonstrate that EPS-block geofoam can contribute to cost-effective and successful slope stabilization and repair. For example, EPS-block geofoam was selected by state DOT representatives or their representatives over a partial or total slide material removal and replacement with another earth material during the Colorado DOT (CDOT) Highway 160 (Yeh and Gilmore, 1992), New York State DOT (NYSDOT) State Route 23A (Jutkofsky 1998; Jutkofsky et al., 2000), and Wisconsin Bayfield County Trunk Highway A (Reuter and Rutz, 2000; Reuter, 2001) projects because the removal and replacement procedure was too costly and because of right-of-way limitations, concerns with impacting adjacent environmentally sensitive areas, concerns with the need to implement an extensive temporary dewatering system during the removal and replacement procedure, and the need to close the road during the removal and replacement procedure. The CDOT Highway 160 project also demonstrated that stabilizing a slope with EPS blocks can be especially cost effective in comparison with traditional earth retention systems.

The Alabama DOT (ALDOT) State Route 44 (Alabama DOT, 2004) project showed that the lower density of EPS blocks compared with other types of lightweight fills such as expanded shale, sawdust, and wood chips can yield a slope with the desired stability while the alternative lightweight fill materials cannot. The CDOT Highway 160 project also demonstrated that EPS blocks can be placed during the winter in cold weather climates when the water level may be the lowest, thus minimizing the need for an extensive temporary dewatering system during construction.

All four case histories included the use of a drainage system below the EPS blocks to prevent water from accumulating above the bottom of the EPS blocks and, in some cases, incorporated a drainage system between the adjacent upper slope material and the EPS blocks to collect and divert seepage water, thereby alleviating seepage pressures. Therefore, these case histories substantiate the recommendation included in the proposed design procedure of EPS-block geofoam slope systems that all EPS-block geofoam slope systems incorporate drainage systems to alleviate the need to consider and design for hydrostatic uplift (flotation) and translation due to water. Therefore, the hydrostatic uplift and translation due to water failure mechanisms are not included in the recommended design procedure shown in Figure 13.

The literature search performed as part of this study revealed that unlike the use of EPS-block geofoam for stand-alone embankments over soft ground, the U.S. case history experience with EPS-block geofoam in slope stabilization is limited. However, it is anticipated that the results of this project will facilitate the use of EPS-block geofoam for slope stabilization and repair in the United States and, consequently, designers involved with slope stabilization and repair will consider EPS-block geofoam as an alternative to slope stabilization more in the future than they have in the past.

In addition to a permanent drainage system, a temporary dewatering and drainage system may be required during construction to prevent flotation of the EPS blocks caused by water collecting in and around the area where the EPS blocks are being placed. Additionally, adequate overburden such as the use of "soft" weights should be applied to the top of the blocks to prevent the blocks from being picked up or displaced by high winds.

One issue that was raised as part of a slide correction project involved the payment quantity of EPS block versus backfill material at the interface between the EPS blocks and the adjacent cut slope. To alleviate this potential pay quantity discrepancy, it is recommended that the drawings specifically show the limits of EPS block placement along the EPS block and adjacent earth slope.

When necessary, an EPS-block geofoam fill can be constructed in phases, allowing one portion of the fill to be completed before beginning construction on the next portion. The advantage of this approach is that it can eliminate the need to completely close down an existing roadway in order to repair the unstable portion of a slope.

RECOMMENDED EPS-BLOCK GEOFOAM STANDARD FOR SLOPE STABILITY APPLICATIONS

A recommended standard for the use of EPS-block geofoam for lightweight fill in slope stabilization is included in Appendix F of the NCHRP Project 24-11(02) final report. The objective during this current project was to modify the NCHRP Project 24-11(01) standard that is applicable to stand-alone embankments over soft ground to make it specific to geofoam usage in slope stability applications. The NCHRP Project 24-11(02) standard included in Appendix F contains six key revisions from the NCHRP Project 24-11(01) standard:

1. A commentary section was added.
2. The use of different minimum allowable density values for individual manufacturing QC/manufacturing QA (MQC/MQA) test specimens versus a higher nominal or average density of the block as a whole was eliminated so that both the block as a whole and any test specimen from within that block meet the same criteria.
3. The minimum allowable values for compressive strength were increased to reflect the increase in these values included in ASTM D 6817 (American Society for Testing and Materials, 2007).
4. The requirements for flexural strength were increased to be consistent with the change in unifying block and test-specimen densities.
5. The wording related to the small-strain modulus was changed from "Initial Tangent Young's Modulus" to "Initial Secant Young's Modulus" simply to correct semantics.
6. Two new, additional types were added: EPS130 and EPS160.

The primary issue related to the recommended material and construction standard included in the NCHRP Project 24-11(01) reports—*NCHRP Report 529* and *NCHRP Web Document 65*—that was evident from the replies to the project questionnaire included in Appendix A of the NCHRP Project 24-11(02) final report is the current confusion between the NCHRP–recommended standard and the ASTM D 6817 material properties. However, based on the consideration of knowledge acquired over the approximately 60 years that EPS has existed as a construction material and the decade of actual project use and experience using the standard for stand-alone embankments included in *NCHRP Report 529* and *NCHRP Web Document 65,* the standards developed for the past and current NCHRP studies are reasonable when implemented properly in practice. Proper implementation includes MQC/MQA laboratory testing performed in accordance with well-established ASTM protocols for test-specimen conditioning prior to testing, numerical correction of all stress-strain curves for machine compression, and graphical correction of stress-strains for initial concavity as necessary.

As noted in a recent article that appeared in *Geo-Strata* magazine, although alignment of the two standards is preferred, the immediate need consists of better educating stakeholders on the basis, benefits, and limitations of both standards for structural and non-structural applications (Nichols 2008).

ECONOMIC ANALYSIS

A review of existing available EPS-block geofoam cost data indicates that EPS-block geofoam prices vary widely and that the price of EPS blocks have substantially increased recently due to the substantial increase in the price of oil. Therefore, a draft price adjustment contract special provision similar to the special provisions that DOTs have used for other construction materials such as bituminous asphalt binder was developed as part of this project and is included in Appendix I of the NCHRP Project 24-11(02) final report. The purpose of the adjustment contract special provision is to minimize the impact of short-term oil price fluctuations on the cost of EPS-block geofoam during multi-phased projects.

In an effort to assist designers with designing a cost-efficient EPS-block geofoam slope, the recommended design procedure for the use of EPS blocks in slopes considers a pavement system with the minimum required thickness, a fill mass with the minimum thickness of EPS-block geofoam, and the use of an EPS block with the lowest possible density. Therefore, the design procedure will produce a technically and cost-efficient design, but, in addition to the cost of the EPS blocks, the overall intangible benefits that the use of EPS-block geofoam can contribute should also be considered as part of the slope stabilization decisionmaking process. An in-depth discussion of these benefits as well as other issues related to the costs associated with EPS-block geofoam construction is provided in Chapter 8 of the NCHRP Project 24-11(02) final report and in *NCHRP Web Document 65* (Stark et al. 2004b).

When attempting to evaluate the feasibility of using EPS-block geofoam for a slope stabilization project, it is important to consider some of the unique characteristics of EPS-block geofoam as a construction material. For example, experience has demonstrated that EPS-block geofoam can be placed quickly. Once the site is prepared, the actual process of moving and positioning the EPS blocks requires minimal equipment and labor. EPS-block geofoam blocks can be transported and placed easily, even at many project sites that would be inaccessible to heavy equipment. Although some specific safety measures may have to be implemented, the placement of EPS blocks can be continued in almost any kind of weather, whereas many other slope stabilization methods may be delayed by rain or snow. The use of EPS-block geofoam may also facilitate phased construction and may minimize disruption to traffic by eliminating the need to close an existing roadway in order to repair the unstable portion of a slope or to widen an existing embankment.

DOTs are particularly interested in the benefit of the accelerated construction that EPS-block geofoam can provide when constructing embankments over soft foundation soils. In June 2002, FHWA in a joint effort with AASHTO organized a geotechnical engineering scanning tour of Europe (AASHTO and FHWA, 2002). The purpose of the European scanning tour was to identify and evaluate innovative European technology for accelerated construction and rehabilitation of bridge and embankment foundations. Lightweight fills is one of the technologies that was evaluated. One of the preliminary findings of the scanning project is that lightweight fills, such as geofoam, is an attractive alternative to surcharging soft soil foundations because the requirement of preloading the foundation soil can possibly be eliminated and, therefore, construction can be accelerated.

Another important consideration is the fact that EPS-block geofoam is a manufactured construction material that can be produced by the molder and then stockpiled at a designated site until it is needed. A DOT agency could potentially store a supply of EPS blocks that could be used for emergency landslide mitigation or repair. Also, EPS blocks can be molded in advance of the actual placement date and can be either transported immediately when needed or stockpiled at the site for immediate use. Thus, the use of EPS blocks in slope application projects can easily contribute to an accelerated construction schedule.

The material cost per volume of EPS-block geofoam is greater than most other types of lightweight fills and conventional soil fill. However, if the intangible benefits of using geofoam are included in the cost analysis—for example, reduced field installation and construction costs, shorter time roadway is not in service, and minimum field quality-control testing—geofoam is a cost-effective alternative to constructing roadway embankments over soft ground. On many projects, the overall immediate and long-term benefits and lower construction cost of using EPS-block geofoam more than compensate for the fact that its material unit cost is usually greater than that of traditional earth fill materials.

When performing an analysis to compare EPS-block geofoam with other potential slope stabilization alternatives, both tangible and intangible benefits of utilizing EPS-block geofoam should be considered when evaluating it as a potential alternative for a slope construction project. The benefit of accelerated construction that the use of EPS-block geofoam can provide has been a key contribution to the decision to use EPS-block geofoam in projects such as the I-15 reconstruction project in Salt Lake City; the CA/T Project in Boston; and the I-95/Route 1 Interchange (Woodrow Wilson Bridge Replacement) in Alexandria, VA (Nichols 2008). Therefore, the benefit of accelerated construction that the use of EPS-block geofoam can provide should be evaluated since it has been a key factor in the decision to use EPS-block geofoam in recent projects in the United States.

The wide variance in price of EPS-block geofoam is perhaps one of the greatest hindrances to the further adoption of EPS-block geofoam in the United States. This wide variance in price may be attributed to the number of potential factors that can impact the cost of EPS-block geofoam. These potential factors are summarized in Chapter 8 of the NCHRP Project 24-11(02) final report and include factors related to manufacturing, design, and construction.

SUMMARY

A major transportation problem in the United States is that current highway capacity is insufficient to meet the growing demand, so new roadway alignments and/or widening of existing roadway embankments will be required to solve the current and future highway capacity problem. It is anticipated that the potential for landslides—which currently pose a major geologic hazard in the United States—will increase as new roadway alignments are constructed and/or existing roadway embankments are widened. EPS-block geofoam is a unique lightweight fill material that can provide a safe and economical solution to slope stabilization and repair.

Benefits of utilizing EPS-block geofoam as a lightweight fill material include the following:

- Ease of construction,
- Possible contribution to accelerated construction,
- Ability to easily implement phased construction,
- Entire slide surface does not have to be removed because of the low driving stresses,
- Can be readily stored for use in emergency slope stabilization repairs,
- Ability to reuse EPS blocks utilized in temporary fills,
- Ability to be placed in adverse weather conditions,
- Possible elimination of the need for surcharging and staged construction,
- Decreased maintenance costs as a result of less settlement from the low density of EPS-block geofoam as well as excellent durability,
- Alleviation of the need to acquire additional right-of-way for traditional slope stabilization methods because of the ease with which EPS-block geofoam can be used to construct vertical-sided fills,
- Reduction of lateral stress on bridge approach abutments,
- Excellent durability,
- Potential construction without utility relocation, and
- Excellent seismic behavior.

The benefit of accelerated construction that the use of EPS-block geofoam can provide was a key factor in the decision to use EPS-block geofoam in projects such as the I-15 reconstruction project in Salt Lake City; the CA/T Project in Boston; and the I-95/Route 1 Interchange (Woodrow Wilson Bridge Replacement) in Alexandria, VA (Nichols 2008). EPS blocks utilized in slope stabilization and repair may not support a pavement system or heavy structural loads, so the potential to utilize EPS blocks with recycled EPS exists. The use of recycled EPS blocks would be an attractive “green” product that reduces waste by recycling polystyrene scrap and would also reduce the raw materials costs in the production of EPS (Horvath 2008).

Although the use of EPS-block geofoam for the function of lightweight fill in stand-alone embankments and bridge approaches over soft ground has increased since the completion of NCHRP Project 24-11(01), an additional application of EPS-block geofoam for the function of lightweight fill that has not been extensively utilized in the United States but has been commonly used in Japan is in slope stabilization applications. Therefore, a need existed in the United States to develop formal and detailed design documents, design guideline, and an appropriate material and construction standard for use of EPS-block geofoam for slope stabilization projects. The slope stabilization projects include new roadways as well as repair of existing roadways that have been damaged by slope instability or movement. This need resulted in the current NCHRP Project 24-11(02), the results of which are summarized in this digest.

The overall objective of this research was to develop a comprehensive document that provides both state-of-the-art knowledge and state-of-practice design guidance for engineers to facilitate use of EPS-block geofoam for the function of lightweight fill in slope stability applications. The completed research consists of the following five primary research products: (1) summary of relevant engineering properties, (2) a comprehensive design guideline, (3) a material and construction standard, (4) economic data, and (5) a detailed numerical example. In addition to the five primary research products listed above, an overview of construction tasks that are frequently encountered during EPS-block geofoam slope projects and a summary of four case histories that provide examples of cost-effective and successful EPS-block geofoam slope stabilization projects completed in the United States is included the NCHRP Project 24-11(02) final report.

The general consensus that was reached at the first *International Workshop on Lightweight Geo-Materials* held March 26 and 27, 2002, in Tokyo is that although new weight-reduction techniques for decreasing applied loads have recently been developed, standardization of design and construction methods is required (“A Report on the *International Workshop on Lightweight Geo-Materials*” 2002). The research results from NCHRP Project 24-11(01), in conjunction with the results of this project, standardize the design and construction guidelines for the use of EPS-block geofoam in various U.S. highway applications.

The purpose of this report is to provide those who have primary involvement with roadway embankment projects—design professionals, manufacturers/suppliers, contractors, regulators, and owners—with design guidance for use of EPS-block geofoam in slope stability applications. The end users of the research include engineers who perform the design and develop specifications and owners, including FHWA, state DOTs, and local county and city transportation departments that own, operate, and maintain the roadway.

An example of the extensive use of the NCHRP Project 24-11(01) research results related to stand-alone EPS-block geofoam embankments overlying soft ground is the large use of EPS-block geofoam on the (CA/T) project in Boston (Riad 2005; Riad et al. 2004; Riad et al. 2003; Riad and Horvath 2004). This project is the first major project to use the NCHRP Project 24-11(01) research results in practice. Another project that utilized the NCHRP results is the I-95/Route 1 Interchange (Woodrow Wilson Bridge Replacement) in Alexandria, VA. It is anticipated that the deliverables of this NCHRP Project 24-11(02) study related to EPS-block geofoam in slope stabilization and repair will also be used and contribute to solving the major geologic hazard of landslides, which are expected to increase as new roadway alignments are constructed and/or existing roadway embankments are widened as part of the effort to meet the growing demand of highway capacity in the United States.

RESOURCES FOR FURTHER INFORMATION

The contractor’s final report of NCHRP Project 24-11(02), “Guidelines for Geofoam Applications in Slope Stability Projects” is available via TRB.org/NCHRP by linking to the project page. The research results of NCHRP Project 24-11(01), “Guidelines for Geofoam Applications in Embankment Projects” are presented in *NCHRP Report 529* and *NCHRP Web Document 65,* which are also available on the TRB website (TRB.org). *NCHRP Report 529* includes only the recommended design guideline and the recommended material and construction standard for use of geofoam in stand-alone roadway embankments. *NCHRP Web Document 65* includes the background and analyses used to develop the recommended design guideline and material and construction standard as well as a summary of the engineering properties of EPS-block geofoam and an economic analysis of geofoam versus other lightweight fill materials.

REFERENCES

"A Report on the *International Workshop on Lightweight Geo-Materials"* (2002). *IGS News,* 9.

AASHTO and FHWA (2002). "2002 Scanning Project Innovative Technology for Accelerated Construction of Bridge and Embankment Foundations." www.fhwa.dot.gov/bridge/bescan.htm, (25 September, 2002).

Alabama DOT (2004). "Foundation Report: ER-6147(4) Slide Correction on AL 44 At MP 6.4, Marion County."

American Society for Testing and Materials (2007). "Standard Specification for Rigid, Cellular Polystyrene Geofoam." D *6817-07,* Vol. 04.13, West Conshohocken, PA.

Arellano, D., and Stark, T. D. (2009a). "Load Bearing Analysis of EPS-Block Geofoam Embankments." *8th International Conference on the Bearing Capacity of Roads, Railways and Airfields*, Champaign, IL, USA, CRC Press, New York, Vol. 1, pp. 981–990.

Arellano, D., Zarrabi, M., Jafari, N. H., and Bailey, L. J. (2009b). "Geosynthetic Aggregate Drainage Systems: Preliminary Large-Scale Laboratory Test Results for Expanded Recycled Polystyrene." *Geosynthetics 2009,* Salt Lake City, UT.

Arellano, D., Tatum, J.B., Stark, T.D., Horvath, J.S., Leshchinsky, D. (2010). "A Framework for the Design Guideline for EPS-Block Geofoam in Slope Stabilization and Repair," *Transportation Research Record 2170,* Transportation Research Board of the National Academies, Washington D.C., pp. 100–108.

Arellano, D., Stark, T.D., Horvath, J.S., Leshchinsky, D., Kafash, M.H., Wang, C. (2011). "Overview of NCHRP Design Guideline for EPS-Block Geofoam in Slope Stabilization," *Proceedings of the 4th International Conference on the use of Geofoam Blocks in Construction Applications,* EPS 2011 Norway, June 5–8, 2011.

Byrne, R. J., Cotton, D., Porterfield, J., Wolschlag, C., and Ueblacker, G. (1998). "Manual for Design and Construction Monitoring of Soil Nail Walls." *FHWA-SA-96-069R,* FHWA, Washington, D.C., 530.

Day, R. W. (2002). *Geotechnical Earthquake Engineering Handbook,* McGraw-Hill, New York.

Elias, V., Christopher, B. R., and Berg, R. R. (2001). "Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design & Construction Guidelines." *FHWA-NHI-00-043,* National Highway Institute, Washington, D.C., 394.

FHWA (2006). "Priority, Market-Ready Technologies and Innovations List: Expanded Polystyrene (EPS) Geofoam." www.fhwa.dot.gov/engineering/geotech/research/bescan.cfm.

Hopkins, T.C., Allen, D.L., Deen, R.C., and Grayson, C.G. (1988). "Slope Maintenance and Slide Restoration: Participant Manual." FHWA, ed., The University of Kentucky Transportation Center, Lexington, 300 p.

Horvath, J. S. (1995). *Geofoam Geosynthetic,* Horvath Engineering, P.C., Scarsdale, NY.

Horvath, J. S. (1999). "Lessons Learned from Failures Involving Geofoam in Roads and Embankments." *Research Report No. CE/GE-99-1,* Manhattan College, Bronx, NY, 18.

Horvath, J. S. (2008). "Levee Alternative." Civil Engineering, pp. 72–77.

Jutkofsky, W. S. (1998). "Geofoam Stabilization of an Embankment Slope, A Case Study of Route 23A in the Town of Jewett, Greene County." Geotechnical Engineering Bureau, New York State Department of Transportation, Albany, NY, 42.

Jutkofsky, W. S., Sung, J. T., and Negussey, D. (2000). "Stabilization of an Embankment Slope with Geofoam." *Transportation Research Record 1736,* Transportation Research Board, National Research Council, Washington D.C., pp. 94–102.

Lazarte, C. A., Elias, V., Espinoza, R. D., and Sabatini, P. J. (2003). "Geotechnical Engineering Circular No. 7: Soil Nail Walls." *FHWA0-IF-03-017,* FHWA, Washington, D.C.

Nichols, S. C. (2008). "Embankments on Soft Ground? Don't Stress It." *Geo-Strata,* pp. 19–24.

Reuter, G., and Rutz, J. (2000). "A Lightweight Solution for Landslide Stabilization." *Geotechnical Fabrics Report,* pp. 42–43.

Reuter, G. R. (2001). "Use of Geofoam for Landslide Stabilization-CTH 'A', Bayfield County, Wisconsin," *Proceedings, EPS Geofoam 2001: 3rd International Conference,* Salt Lake City, UT.

Riad, H. L. (2005). "EPS Structures Innovations on Central Artery/Tunnel (CA/T) Project." *2005 BSCES ASCE Geo-Institute Seminar on Recent Advances in Geotechnical Engineering,* Waltham, MA.

Riad, H. L., and Horvath, J. S. (2004). "Analysis and Design of EPS-Geofoam Embankments for Seismic Loading." *Geotechnical Engineering for Transportation Projects (GSP 126): Proceedings of Geo-Trans 2004,* M. K. Yegian, and E. Kavazanjian, eds., ASCE/GEO Institute, Reston, VA, pp. 2028–2037.

Riad, H. L., Anthony, L. R., Peter, W. O., and John, S. H. (2003). "Expanded Polystyrene (EPS) Geofoam for Road Embankments and Other Lightweight Fills in Urban Environments." Soil and Rock America, 12th Pan-American Conference on Soil Mechanics and Geotechnical Engineering and 39th U.S. Rock Mechanics Symposium, 2003, 6.

Riad, H. L., Anthony, L. R., Peter, W. O., David, A. D. A., and John, S. H. (2004). "Design of Lightweight Fills for Road Embankments on Boston's Central Artery/Tunnel Project."

Spiker, E. C., and Gori, P. L. (2003). "National Landslide Hazards Mitigation Strategy—A Framework for Loss Reduction." pubs.usgs.gov/circ/c1244/.

Stark, T. D., Arellano, D., Horvath, J. S., and Leshchinsky, D. (2004a). *NCHRP Report 529: Guideline and Recommended Standard for Geofoam Applications in Highway Embankments.* Transportation Research Board of the National Academies, Washington, D.C. trb.org/publications/nchrp/nchrp_rpt_529.pdf.

Stark, T. D., Arellano, D., Horvath, J. S., and Leshchinsky, D. (2004b). *NCHRP Web Document 65: Geofoam Applications in the Design and Construction of Highway Embankments.* Transportation Research Board of the National Academies, Washington, D.C., trb.org/publications/nchrp/nchrp_w65.pdf.

Thompson, M. J., and White, D. J. (2005). "Review of Stability Berm Alternatives for Environmentally Sensitive Areas." Center for Transportation Research and Education Iowa State University. www.intrans.iastate.edu/reports/berm_stability.pdf, Ames, IA.

Transportation Research Board (1996). *Special Report 247: Landslides: Investigation and Mitigation,* A. K. Turner, and R. L. Schuster, eds., Transportation Research Board, National Research Council, Washington, D.C.

Tsukamoto, H. (1996). "Slope Stabilization by the EPS Method and Its Applications." *Proceedings of the International Symposium on EPS Construction Method (EPS Tokyo '96),* EPS Construction Method Development Organization, Tokyo, Japan, pp. 362–380.

Yeh, S.-T., and Gilmore, J. B. (1992). "Application of EPS for Slide Correction." Proceedings, Stability and Performance of Slopes and Embankments–II; Geotechnical Special Publication No. 31, ASCE, pp. 1444–1456.

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