Interim Design Guideline for EPS-Block Geofoam in Slope Stabilization and Repair

David Arellano, Ph.D., P.E., Assistant Professor
Department of Civil Engineering
The University of Memphis
104 Engineering Science Building
Memphis, Tennessee 31852-3180
Tel: (901) 678-3272
E-mail: darellan@memphis.edu
(Corresponding Author)

John Benjamin Tatum, Graduate Research Assistant
Department of Civil Engineering
The University of Memphis
104 Engineering Science Building
Memphis, Tennessee 31852-3180
Tel: (901) 678-3272
E-mail: jbtatum@memphis.edu

Timothy D. Stark, Ph.D., P.E., Professor
Department of Civil and Environmental Engineering
University of Illinois @Urbana-Champaign
205 N. Mathews MC-250
Urbana, Illinois 61801
Tel: (217) 333-7394
E-mail: tstark@uiuc.edu

John S. Horvath, Ph.D., P.E., Professor
Department of Civil and Environmental Engineering
Manhattan College
Bronx, New York 10471
Tel: (718) 826-7177
E-mail: john.horvath@manhattan.edu

Dov Leshchinsky, Ph.D., Professor
Department of Civil and Environmental Engineering
University of Delaware
Newark, DE 19716
Tel: (302) 831-2446
E-mail: dov@UDel.edu

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ABSTRACT

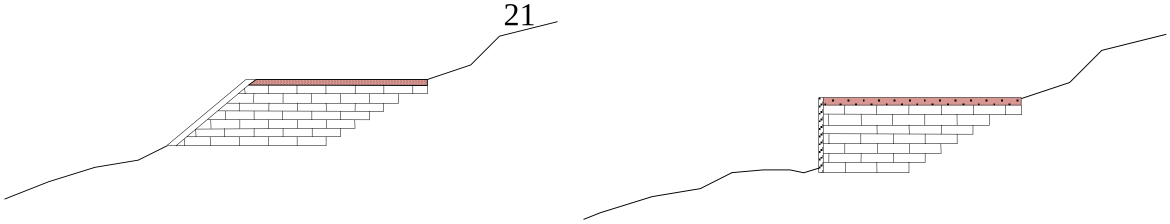
This paper presents an interim design guideline for the use of expanded polystyrene (EPS)-block geofoam for slope stabilization and repair based on the National Cooperative Highway Research Program (NCHRP) Project 24-11(02) Phase I study. The overall objective of this research is to develop a design guideline as well as an appropriate material and construction standard for the use of EPS-block geofoam for the function of lightweight fill in slope stability applications. The recommended interim design methodology is based on an assessment of existing technology and literature. The Phase II work will refine the interim design guideline and address some uncertainties in the current state-of-practice of analyzing various failure mechanisms included in the design procedure. The completed research will consist 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. 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 interim design guideline for EPS-block geofoam can serve as a blueprint for the use of other types of lightweight fills in slope stability applications. The NCHRP Project 24-11(01) and the Project 24-11(02) Phase I research confirmed that EPS-block geofoam is a unique lightweight fill material and can provide a safe and economical solution for slope stabilization and repair.

INTRODUCTION

This paper presents the interim design guideline for use of expanded polystyrene (EPS)-block geofoam for slope stabilization and repair based on the National Cooperative Highway Research Program (NCHRP) Project 24-11(02) Phase I study (*1*). The overall objective of this research is to develop a design guideline as well as an appropriate material and construction standard for the use of EPS-block geofoam as lightweight fill in slope stability applications.

The objective of the previous NCHRP study related to geofoam, Project 24-11(01), was to develop a recommended design guideline and material and construction standard for 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 reports (*2, 3*).

The design guideline included in the NCHRP Project 24-11(01) reports 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. Slope stability applications (sometimes referred to as side-hill fills and the focus of this paper) are shown in Figure 1. As shown in Figure 1, the use of EPS-block geofoam in slope applications can involve a slope-sided fill (Figure 1a) or a vertical-sided fill (Figure 1b). 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 the fill loads on nearby structures.



(a) Slope-sided fill. (**b) Vertical-sided fill (geofoam wall).**

FIGURE 1 Typical EPS-block geofoam applications involving side-hill fills.

An example of the extensive use of the NCHRP Project 24-11(01) deliverables is the large use of EPS-block geofoam on the Central Artery/Tunnel (CA/T) project in Boston, MA. This project is the first major project to use the NCHRP Project 24-11(01) research results in practice (*4*). Another project that utilized the Project 24-11(01) 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, such as the I-15 Reconstruction Project in Salt Lake City, Utah, 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 (*5*) 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.

As part of the Federal Highway Administration's (FHWA's) ongoing Accelerated Construction Technology Transfer Program, the 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 (*6*). The FHWA considers EPS-block geofoam an innovative material and construction technique that can accelerate project schedules and a viable and cost-effective solution to roadway embankment widening and new roadway embankment alignments over soft ground. Thus, EPS-block geofoam is a market-ready technology that can contribute to solving the major highway problem in the U.S. of insufficient highway capacity to meet growing demand.

PROBLEM STATEMENT

A major transportation problem in the U.S. is that current highway capacity is insufficient to meet the growing demand. Therefore, new roadway alignments and/or widening of existing roadway embankments is/will be required to solve the current and future highway capacity problem. As noted by Spiker and Gori (*7*), 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 (*7, 8*). Active seismic activity contributes to the landslide hazard risk in areas such as Alaska, Hawaii, and the Pacific Coast. Spiker and Gori (*7*) indicate that landslides are among the most widespread geologic hazard on earth and estimate damages related to landslides exceed $2 billion annually.

An additional application of EPS-block geofoam for the function of lightweight fill that has not been extensively utilized in the U.S., but has been commonly used in Japan, is in slope stabilization applications. 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 design guideline and the standard included in the 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 U.S. to develop formal and detailed design guideline and appropriate material and construction standard for use of EPS-block geofoam for slope stabilization projects. This need resulted in the current NCHRP Project 24-11(02) and the interim design guideline described 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 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 hazard, 2) reduce the driving forces, or 3) increase the resisting forces.

The use of lightweight fill is a slope stabilization procedure that can be used to reduce the weight of the sliding mass and, thereby, reduce the driving forces of the sliding mass. The lightweight fill materials, especially EPS blocks, also may result in an increase in the resisting forces because the blocks can be stronger than landslide material. The recommended interim design guideline described herein focuses on the use of EPS-block geofoam as a lightweight fill material for slope stabilization and repair.

BASIS OF INTERIM DESIGN GUIDELINE

A review of current slope stability and landslide remediation textbooks (*8*-*12*) revealed a lack of formal design guidelines to design slopes or remediate slides by reducing the weight of the slide mass using lightweight fill. Although a comprehensive design procedure is not available, some of the literature does provide general design guidance for the use of geofoam in slope stability applications (*13*-*15*) and for the use of lightly cemented rubber tires (*16*).

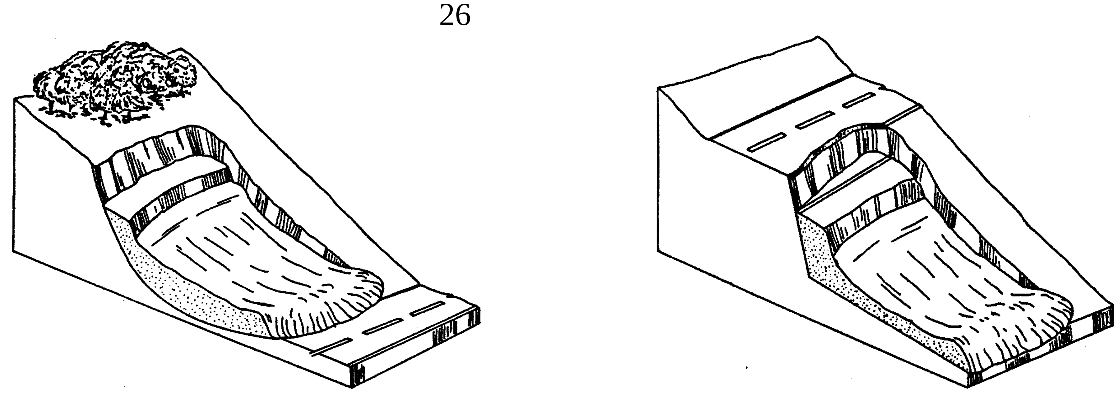
Specific treatment of the use of EPS-block geofoam for slope stabilization in Japan, largely in the mid-1980’s to the mid-1990’s time frame, is discussed in various papers including the proceedings of the 1996 International Symposium on EPS held in Tokyo, Japan (*17*). Tsukamoto (*15*) introduced a design procedure for the use of EPS in slope stabilization. This Japanese design procedure includes many of the steps included in the NCHRP 24-11(01) recommended design guideline for stand-alone EPS-block geofoam embankments over soft soil (*2, 3*). Therefore, the 24-11(01) recommended design procedure was used as the preliminary basis for the slope design guideline and was modified to incorporate slope design considerations. Although Tsukamoto (*15*) introduced a design procedure, he did not provide guidelines or procedures to perform these steps. Therefore, one challenge of the Phase I work was to identify potential analysis procedures to perform the design steps.

Because the current state-of-practice of slope stability analysis is based on service load design (SLD), the interim design guideline is based on the SLD approach. Until the inconsistencies with applying the Load and Resistance Factor Design LRFD methodology to slope stability analysis are resolved, an LRFD based design procedure for EPS-block geofoam slopes cannot be developed. Leshchinsky (*18*) provides a more detailed discussion on the problems associated with the use of LRFD in slope stability analysis.

DESIGN PROCEDURE

In the U.S., several slope stabilization projects have involved the use of EPS-block geofoam, such as U.S. Highway 160 in Colorado (*19*), State Route 23A in New York (*14, 20, 21*), Bayfield County Trunk Highway A in Wisconsin (*22, 23*), State Route 44 in Alabama (*24*), and a private residence in Seattle, Washington (*25*). In addition to geofoam, a wide variety of other lightweight fill materials, including shredded tires (*26*), wood chips (*27-32*), and pumice (*33*), have also been successfully incorporated into slope stability projects around the world.

These case histories demonstrate that lightweight fill materials can improve slope stability in both soil and rock slopes. Additionally, these case histories indicate that both rotational and translational modes of sliding as shown in Figures 2(a) and 2(b), respectively, can occur in both soil and rock slopes.



(a) Slide above roadway. **(b) Slide below roadway.**

FIGURE 2 Slide above and below roadway (*34*).

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. Figure 2 shows the two possibilities which are a slide above the roadway (Figure 2(a)) and a slide below the roadway that removes some or the entire pavement (Figure 2(b)). Figure 3 shows the recommended design procedure if the existing or proposed roadway is located within the existing or anticipated slide mass <u>and</u> the existing or anticipated slide mass is located below the roadway both of which are shown in Figure 2(b), i.e., the roadway is in or near the head of the slide mass.

Figure 4 shows the modified interim design procedure if the existing or proposed roadway is located outside the limits of the existing or anticipated slide mass <u>and/or</u> the existing or anticipated slide mass is located above the roadway as shown in Figure 2(a), i.e., the roadway is near the toe of the slide mass. 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, the primary difference between the recommended design procedure in Figure 3 and the modified procedure in Figure 4 is that the pavement system failure mode is not included in the modified procedure in Figure 4. 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 7 and 8 of the full design procedure shown in Figure 3, which involves the pavement system, may not be required and is not part of the modified design procedure shown in Figure 4.

Figure 5 shows a design selection diagram that can be used to determine whether to use the complete procedure shown in Figure 3 or the modified design procedure shown in Figure 4. 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. However, 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 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.

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 (*35*) and mechanically stabilized earth walls (*36*). These failure modes are external stability of the overall EPS-block geofoam slope system configuration and internal stability of the fill mass. EPS-block geofoam slope systems may also incorporate a pavement system. Therefore, a third potential failure mode is pavement system failure. The design of an EPS-block geofoam slope system against these three failure modes requires consideration of the interaction between the three major components of an EPS-block slope system shown in Figure 6, i.e., existing slope material, fill mass, and pavement system. The subsequent sections include an overview of these three failure modes.

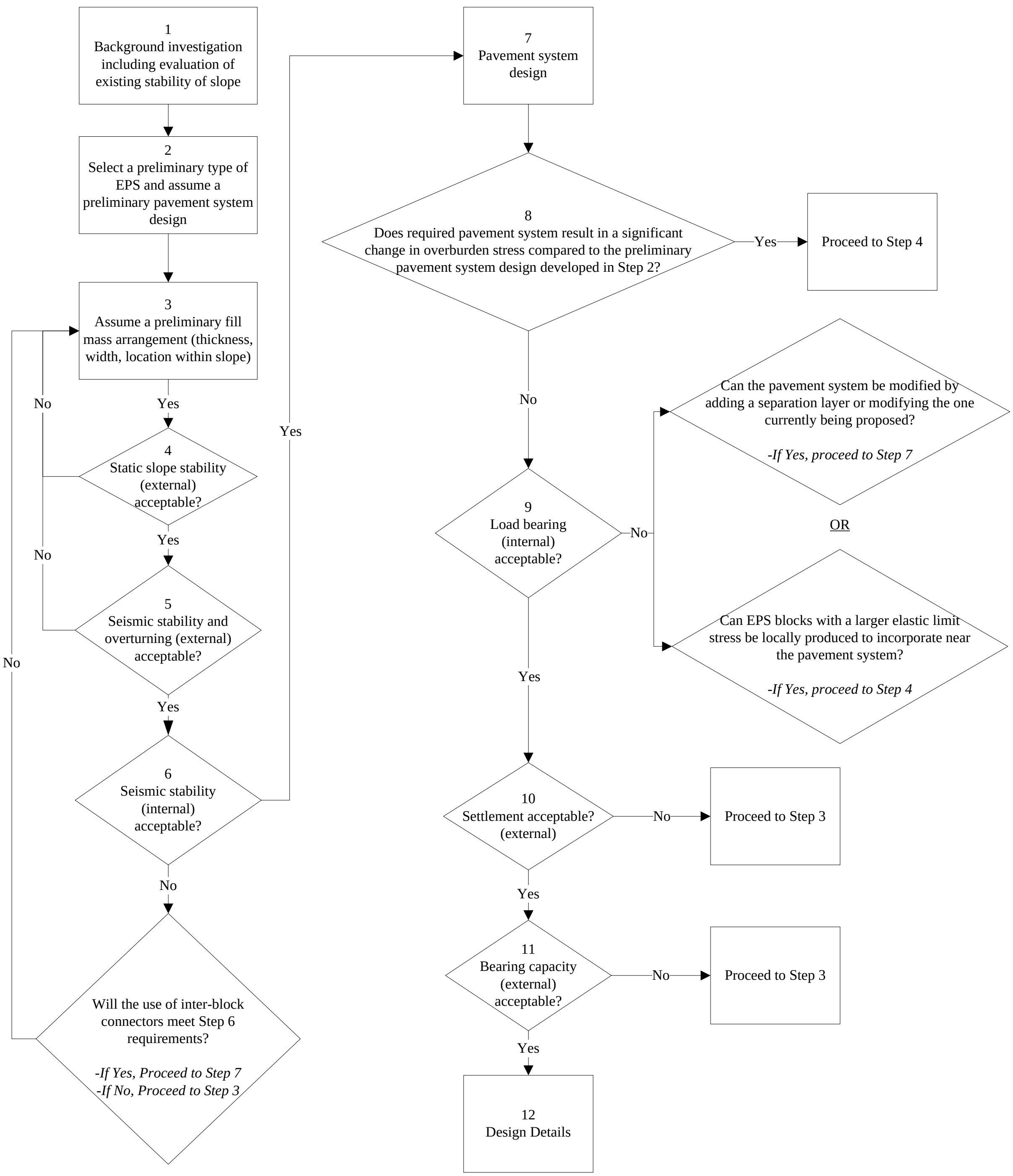


FIGURE 3 Recommended design procedure for the case of the existing or proposed roadway located within the existing or anticipated slide mass <u>and</u> the existing or anticipated slide mass is located below the roadway, i.e. roadway is near the head of the slide mass.

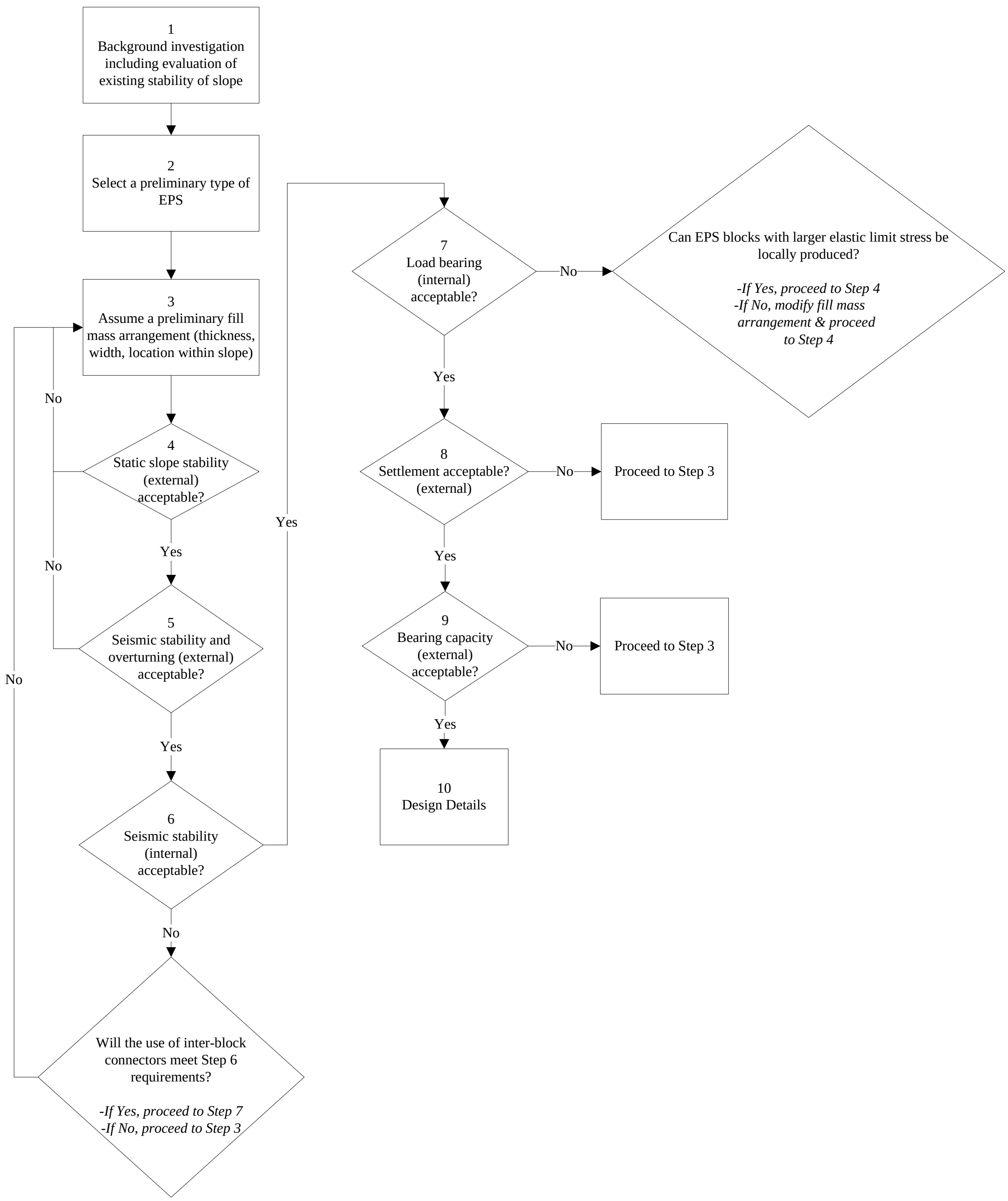


FIGURE 4 Modified design procedure for the case of the existing or proposed roadway located outside the limits of the existing or anticipated slide mass and/or the existing or anticipated slide mass located above the roadway, i.e. roadway is near the toe of the slide mass.

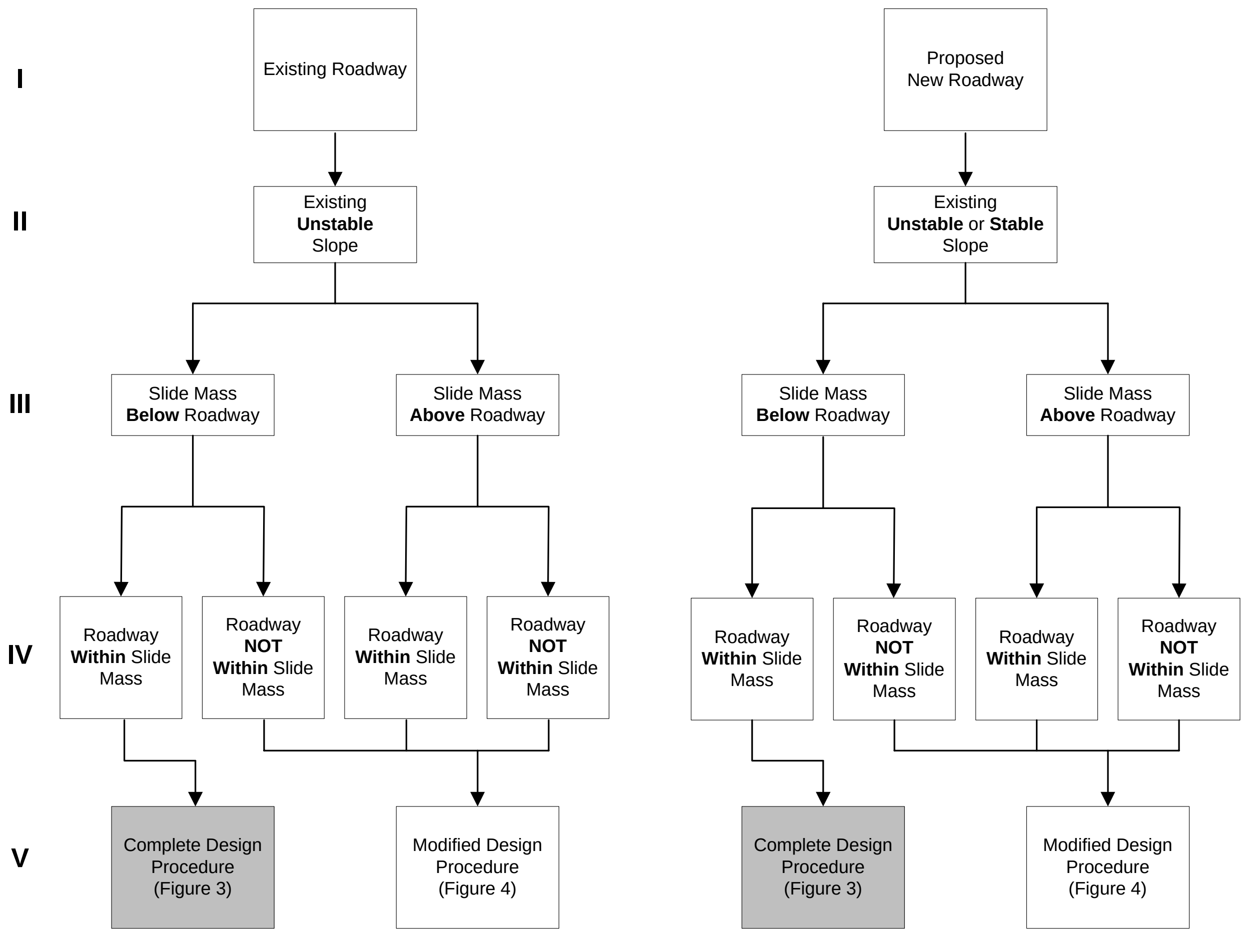


FIGURE 5 Design procedure selection diagram.

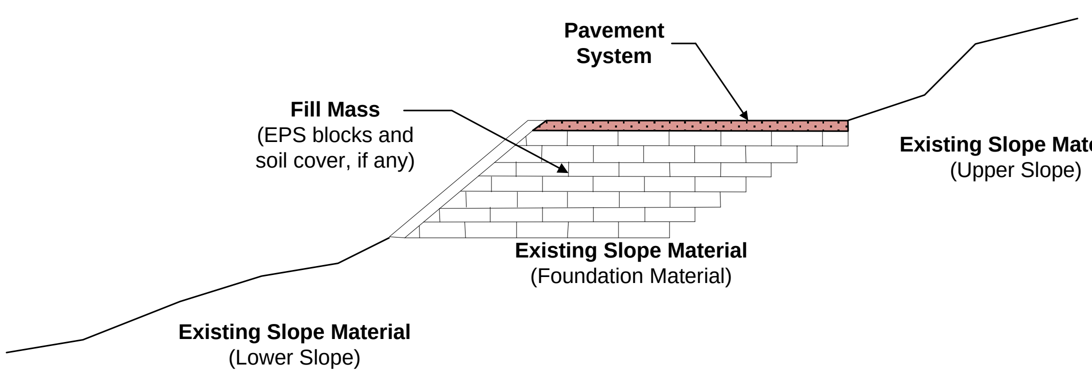


FIGURE 6 Major components of an EPS-block geofoam slope system.

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 well as failure mechanisms that involve both the fill mass and the existing slope material. The latter potential failure surface is similar to the "mixed" failure mechanism identified by Byrne et al. (*37*) 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 24-11(01) design procedure for stand-alone embankments consist 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. Many of the EPS-block geofoam slope case histories evaluated as part of this Project 24-11(02) research 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 and thereby alleviate 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 is part of the design, then analyses for the hydrostatic uplift (flotation) and translation due to water failure mechanisms that are included in the 24-11(01) design procedure for stand-alone embankments are not required in slope applications. Therefore, the hydrostatic uplift and translation due to water failure mechanisms are not included in the interim design procedure for slope applications. In addition to a permanent drainage system, temporary dewatering and drainage systems may need to be considered for construction.

Translation and overturning due to wind is a failure mechanism that is considered in the 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 (*15*). 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 6. Thus, wind loading does not appear to be a likely failure mechanism for EPS-block geofoam slopes. Therefore, the wind loading failure mechanism is not included in the current recommended interim design procedure. However, it is recommended that additional research be performed based on available wind pressure data for structures located on slopes to further evaluate the need to consider wind as a potential failure mechanism.

External failure mechanisms due to seismic loads include slip surfaces through existing slope material only, both the fill mass and existing slope material, horizontal sliding of the entire EPS-block geofoam fill mass, overturning of a vertical-sided embankment, bearing capacity failure of the existing foundation material due to seismic loading and/or a decrease in the shear strength of the foundation material, and earthquake induced settlement of the existing foundation material.

In summary, the external stability failure mechanisms that are included in the proposed interim design procedure consist of static slope stability (Step 4 in Figures 3 and 4), settlement (Step 10 in Figure 3 and Step 8 in Figure 4), and bearing capacity (Step 11 in Figure 3 and Step 9 in Figure 4). Additional failure mechanisms associated with external seismic stability that are included in Step 6 in Figures 3 and 4 consist of seismic slope instability, seismically induced settlement, seismic bearing capacity failure, seismic sliding, and seismic overturning. These external instability design 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 optimize the design to minimize the volume of EPS used yet still satisfy external instability design criteria concerning settlement, bearing capacity, and static and seismic slope stability.

Internal Instability Failure Mode

Internal instability failure mechanisms included in the 24-11(01) design procedure for stand-alone embankments consist 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. Therefore, seismic stability and load bearing of the EPS blocks appear to be the primary internal instability failure mechanisms that need to be considered.

It should be noted that 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 24-11(01) design procedure for stand-alone embankments because there is little or no static driving force imposed by the EPS block fill mass to cause 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 stand-alone 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 was evaluated. 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 stable. Because the EPS fill mass is typically small, it may not be feasible for the EPS fill to directly resist external applied earth forces from the adjacent slope material. Additionally, the interface shear resistance of EPS/EPS interfaces may be low because it is primarily due to the mass of the EPS blocks so the shear resistance between blocks may not be adequate to sustain adjacent earth pressures. Therefore, the interim 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 to resist the applied earth force. Various types of earth retention systems that incorporate EPS blocks are summarized in the interim report as well as in the literature (*1, 13, 15*).

The primary evaluation of internal seismic stability involves determining whether or not 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 interim standard in the interim report (*1*) provides block placement guidelines that 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. Another seismic internal stability failure mechanism that was recognized for stand-alone embankments during the design of the Central Artery/Tunnel (CA/T) project (*38-40*) is load bearing failure due to seismic rocking of the fill mass that contributes to an increase in the vertical normal stress within the EPS-block fill mass. Phase II of the Project 24-1(02) research will include an applicability evaluation of this seismic shaking failure mechanism for slopes.

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 or time-dependent (creep) compression that can lead to excessive settlement of the pavement surface. The load bearing analysis procedure for stand-alone embankments (*2, 3, 41*) is also included in the interim design procedure for slope applications.

In summary, the three internal instability failure mechanisms that are evaluated in the interim design guideline are seismic horizontal sliding and seismic load bearing of the EPS blocks (Step 6 in Figures 3 and 4) and load bearing of the EPS blocks (Step 9 in Figure 3 and Step 7 in Figure 4).

Pavement System Failure Mode

Design of an appropriate pavement system considers 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. Also, when designing the pavement cross-section, some consideration should be given to providing sufficient support, either by direct embedment or structural anchorage, for any road hardware such as guardrails, barriers, median dividers, lighting, signage and utilities. Pavement design recommendations are included in the Project 24-11(01) reports for stand-alone embankments. However, the Phase II research for slope applications will consist of updating the 24-11(01) pavement design recommendations so that the updated recommended pavement design procedures are in alignment with the current AASHTO Mechanistic-Empirical Design Guide (MEPDG) (*42*).

Other Aspects of Design Procedure

The design of an EPS-block geofoam slope system requires consideration of the interaction between the three major components of an EPS-block slope system shown in Figure 6, i.e., external instability, internal instability, and pavement system failure. Because of this interaction, the design procedure involves interconnected analyses between 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. In addition, cost must be considered because EPS-block geofoam is typically more expensive than soil on a cost-per-unit-volume basis for the material alone. The design procedures in Figures 3 and 4 consider 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 proposed design procedure will produce a cost efficient design.

SUMMARY

This paper presents the interim design methodology from the NCHRP Project 24-11(02) interim report (*1*) for use of geofoam for slope stabilization. Two potential design procedures are recommended for the design of EPS-block geofoam slope systems. The complete design procedure shown in Figure 3 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 Figure 2(b). The modified design procedure shown in Figure 4 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 2(a).

The recommended interim design methodology is based on an assessment of existing technology and literature. The Phase II work will refine the interim design guideline and address some uncertainties in the current state-of-practice of analyzing various failure mechanisms included in the design procedure. The completed research will consist 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. Completion of Phase II is scheduled for June 2010.

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 interim design guideline for EPS-block geofoam can serve as a blueprint for the use of other types of lightweight fills in slope stability applications. The NCHRP Project 24-11(01) and the Project 24-11(02) Phase I research confirmed EPS-block geofoam is a unique lightweight fill material that can provide a safe and economical solution for slope stabilization and repair.

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