

Overview of NCHRP Design Guideline for EPS-Block Geofam in Slope Stabilization and Repair

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

Timothy D. Stark, Ph.D., P.E., Professor
Department of Civil and Environmental Engineering
University of Illinois at 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

Masood H. Kafash & Chuanqi Wang, Graduate Research Assistants
Department of Civil Engineering
The University of Memphis
E-mail: mhssnzd@memphis.edu & cwang1@memphis.edu

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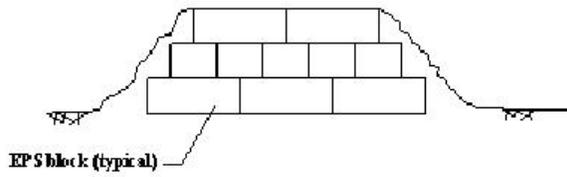
ABSTRACT

This paper presents an overview of the design guideline for the use of expanded polystyrene (EPS)-block geofoam for slope stabilization and repair applications based on the results of National Cooperative Highway Research Program (NCHRP) Project 24-11(02). This study is the second part of a two-part study on EPS-block geofoam. The first study was performed under NCHRP Project 24-11(01) and produced a design guideline for use of EPS blocks in stand-alone roadway embankments and bridge approaches over soft ground. The design of an EPS-block geofoam slope system considers the interaction of three major components: existing slope material, fill mass, and pavement system. The three potential failure modes that can occur due to interaction of these three primary components of an EPS slope system include external instability of the overall EPS-block geofoam slope system, internal instability of the EPS fill mass, and pavement system failure. This paper presents the failure mechanisms that are evaluated within each of these three potential failure modes and included in the design guideline. The NCHRP 24-11(02) study confirmed that EPS-block geofoam is a unique lightweight fill material that provides a safe and economical solution for slope stabilization and repair. However, the NCHRP 24-11 studies revealed important analysis and design differences between the use of EPS blocks for slope stabilization and stand-alone embankments. For example, the road pavement may not overlie the portion of the slope stabilization where the EPS blocks are placed. Therefore, load conditions on the EPS blocks may be such that low density or recycled EPS blocks can be used, which can contribute to a more cost-effective design.

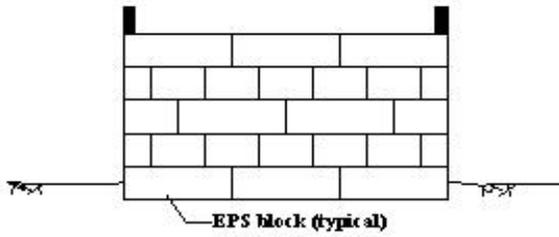
INTRODUCTION

This paper presents an overview of the design procedure included in the design guideline for use of expanded polystyrene (EPS)-block geofoam for slope stabilization and repair based on the results of National Cooperative Highway Research Program (NCHRP) Project 24-11(02) Phase II (Arellano et al. 2011). The overall objective of this study is to develop a design guideline for the use of EPS-block geofoam for slope stabilization and repair. This study is the second part of a two-part study on EPS-block geofoam. The first study was performed under NCHRP Project 24-11(01) titled “Guidelines for Geofoam Applications in Embankment Projects.” The objective of the first study was to develop a recommended design guideline for the use of EPS-block geofoam in stand-alone embankments and bridge approaches over soft ground.

The recommended design guideline included in the NCHRP Project 24-11(01) reports (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 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.

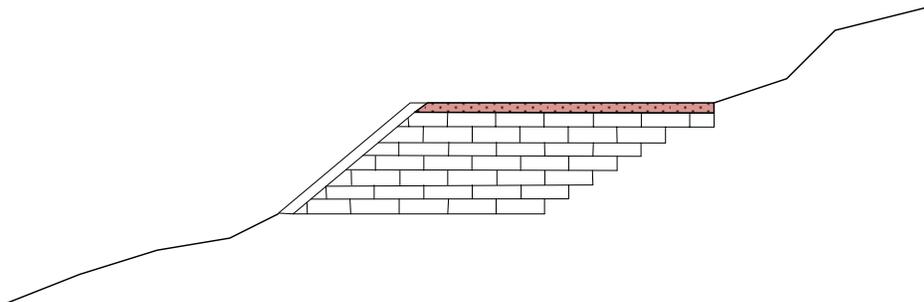


(a) *Slope-sided fill.*

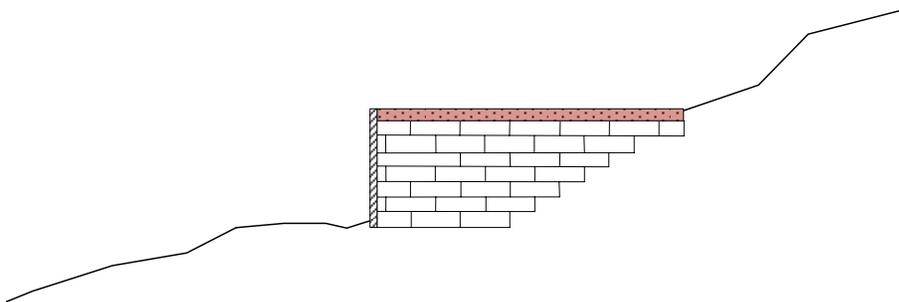


(b) *Vertical-sided fill (Geofoam wall).*

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.

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 problem, 2) reduce the driving forces, or 3) increase the resisting forces. The use of EPS blocks for slope stabilization is a method that is part of the second classification that involves reducing the driving forces.

A review of current slope stability and landslide remediation textbooks (Abramson et al. 2002; Cornforth 2005; Duncan and Wright 2005; Transportation Research Board 1996) 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 (Horvath 1995; Negussey 2002; Tsukamoto 1996) and for the use of lightly cemented rubber tires (Lee et al. 2002).

Specific treatment of the use of EPS-block geofoam for slope stabilization work involves projects in Japan, largely in the mid-1980's to the mid-1990's time frame, with much of that work being discussed in various papers included in the proceedings to the 1996 International Symposium on EPS held in Tokyo, Japan (EDO 1996). The Japanese design procedure for the use of EPS for slope stabilization 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. 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 considerations. Although Tsukamoto (1996) introduces design steps for the use of EPS for slope stabilization, he does not provide guidelines or procedures to perform these steps. Therefore, one challenge of this NCHRP 24-11 (02) study was to develop analysis procedures to perform the various design steps.

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, i.e., external instability, internal instability, and pavement system failure, that 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 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.

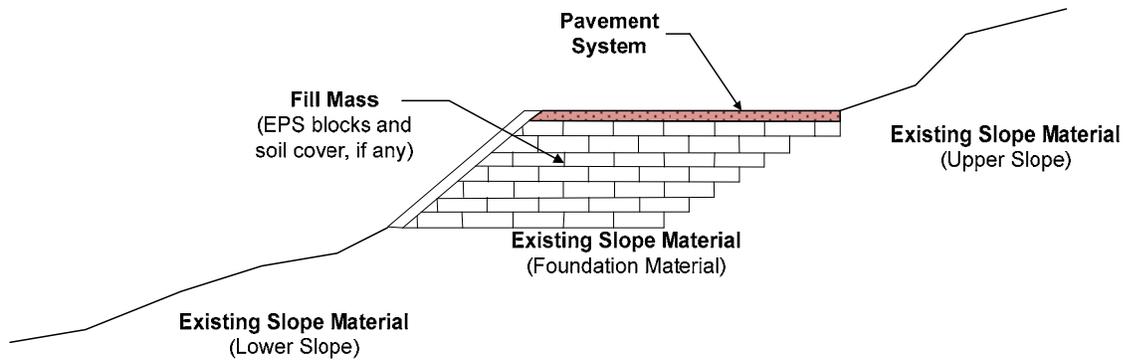


Figure 3. Major components of an EPS-block geofoream slope system.

FAILURE MODES

Overview

Potential failure modes that must be considered during stability evaluation of an EPS-block geofoream 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 geofoream slope systems may also incorporate a pavement system. Therefore 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 geofoream 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 geofoream 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, e.g. mechanically stabilized earth walls (MSEWs) and reinforced soil slopes (RSS) (Elias et al. 2001). Additionally, some of the failure 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.

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 applications

| 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 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

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 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.

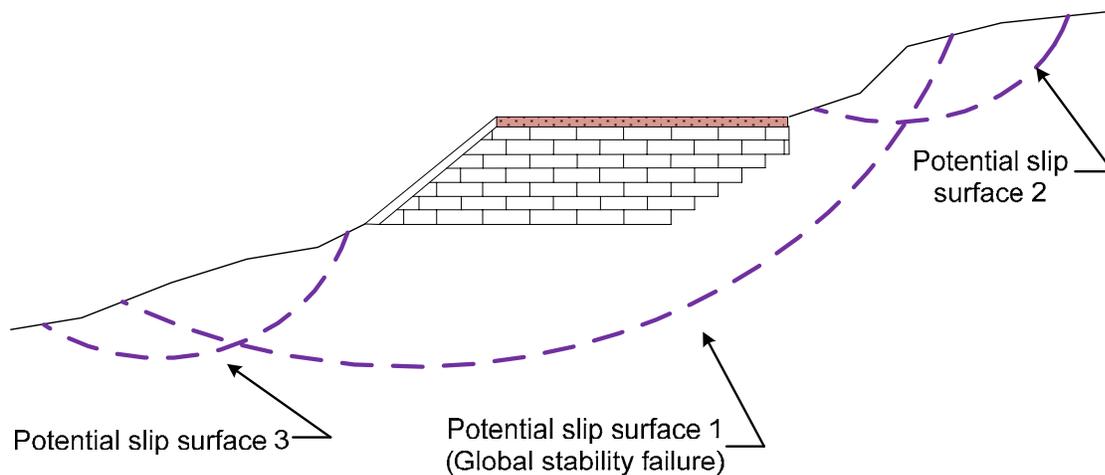


Figure 4. Static and seismic slope stability involving existing soil slope material only.

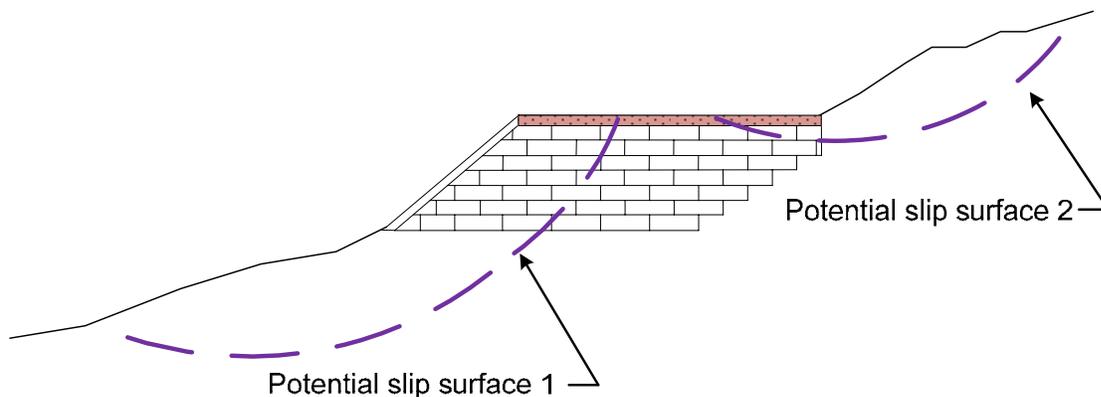


Figure 5. Static and seismic slope stability involving both the fill mass and existing soil slope material.

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 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 that will 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 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. Therefore, 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 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 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.

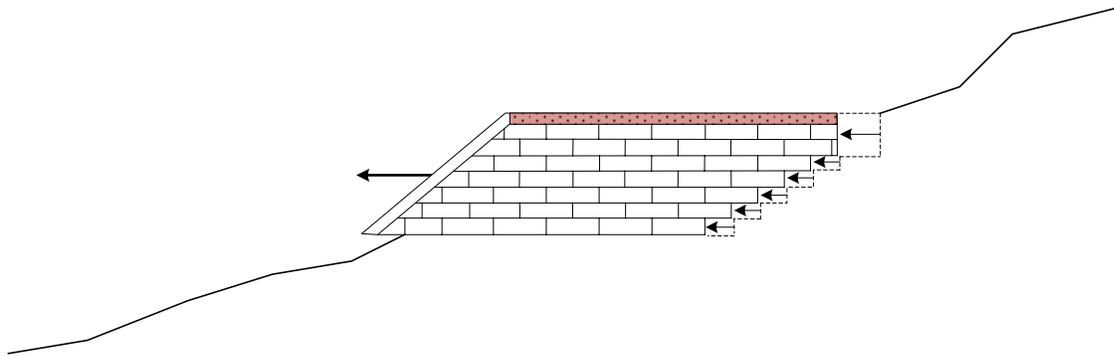


Figure 6. External seismic stability failure involving horizontal sliding of the entire embankment.

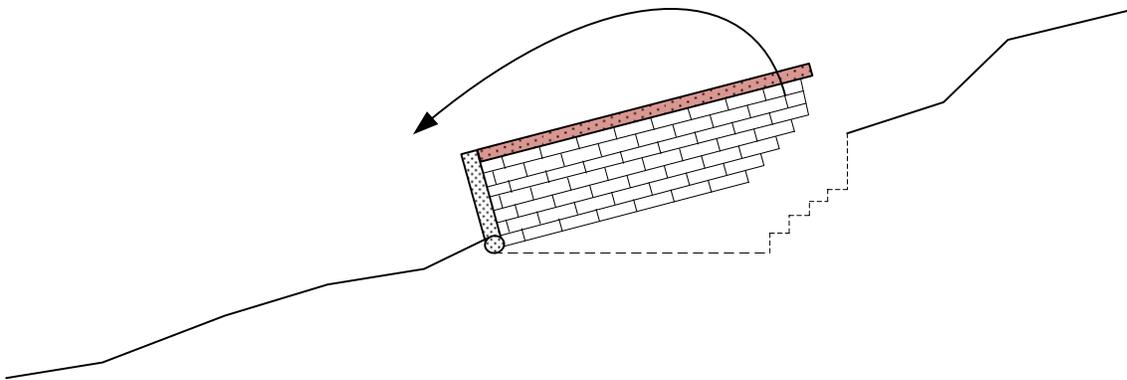


Figure 7. External seismic stability failure involving overturning of an entire vertical embankment about the toe of the embankment.

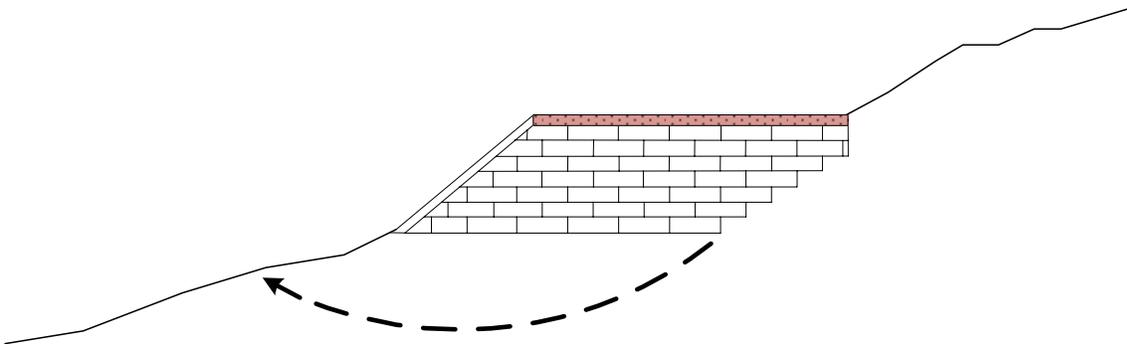


Figure 8. Bearing capacity failure of the embankment due to general shear failure or local shear failure.

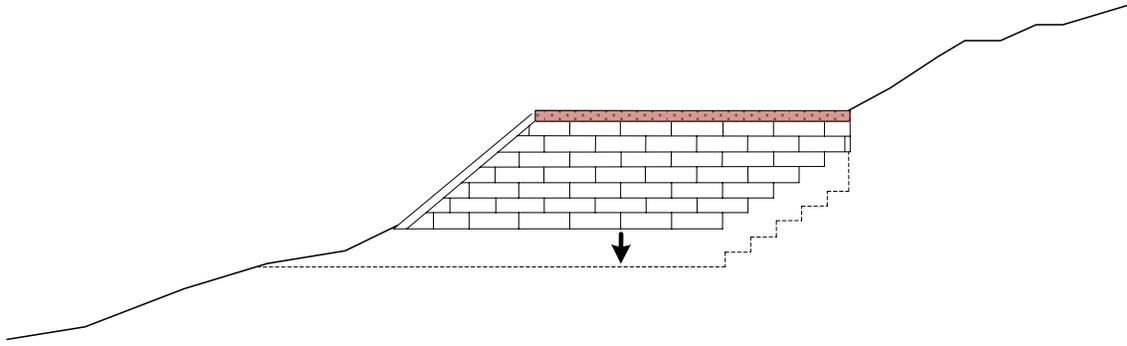


Figure 9. Excessive settlement.

Internal Instability Failure Mode

Design for internal stability considers failure mechanisms within the EPS-block geofill mass. The internal instability failure mechanisms included in the 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 geofill slope systems. The translation due to water failure mechanism is not applicable provided 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 24-11(01) design procedure for stand-alone embankments because there is little or no static 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 geofill 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 geofill slope system to support a portion of the upper adjacent slope.

The primary evaluation of internal seismic stability involves determining whether the geofill 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 2009; 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.

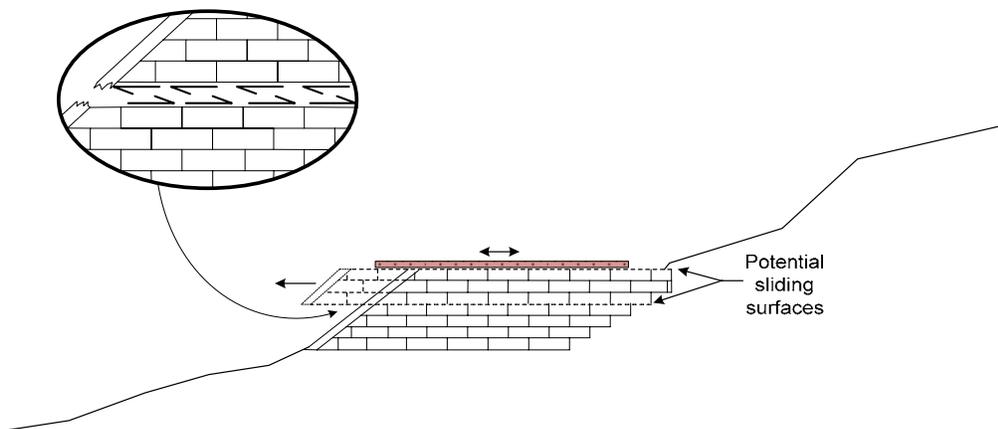


Figure 10. Internal seismic stability failure involving horizontal sliding between blocks and/or between the pavement system and the upper layer of blocks due to seismic loading.

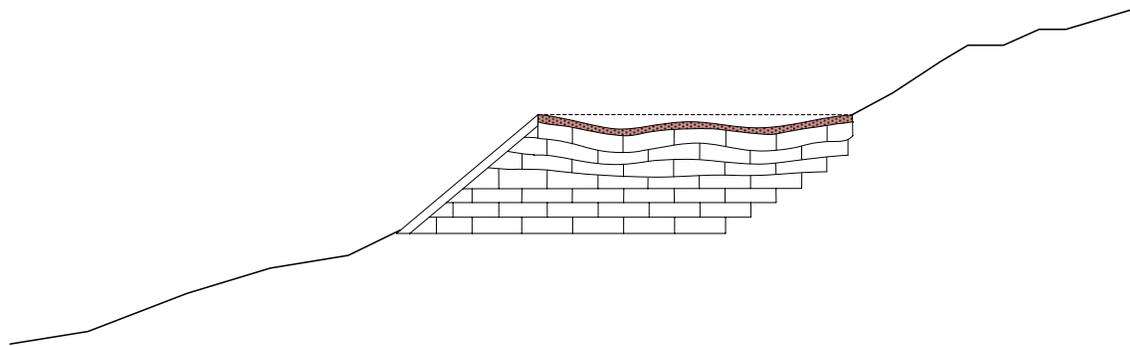


Figure 11. Load bearing failure of the blocks involving excessive vertical deformation.

Pavement System Failure Mode

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, which is an SLS type of failure (Figure 12). 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.

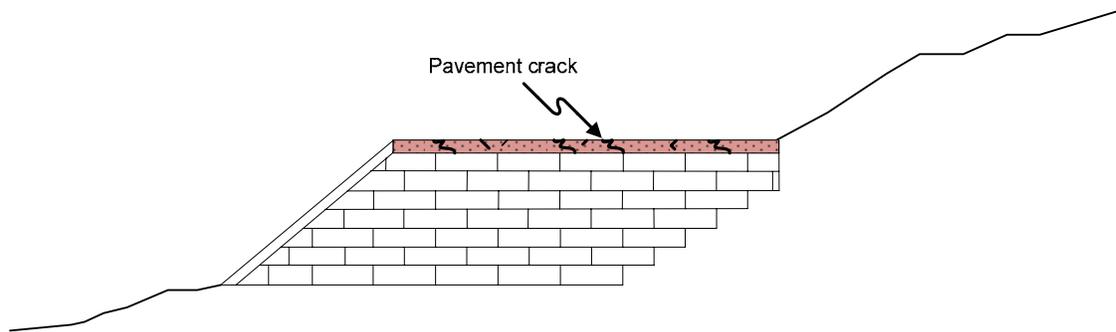


Figure 12. Pavement failure due to cracking.

In summary, the three failure modes that must be considered during stability evaluation of an EPS-block gefoam 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

The design requirements of EPS-block gefoam 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, i.e., slide mass located above the roadway as shown in Figure 13 (a) or slide mass located below the roadway as shown in Figure 13 (b).

Figure 14 shows the recommended design procedure 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 13 (b), i.e., the roadway is near the head of the slide mass.

Figure 15 shows the recommended modified design procedure 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 13 (a), i.e., the roadway is near the toe of the slide mass. It is anticipated that EPS-block gefoam 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 14 and the modified procedure in Figure 15 is that 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 15. 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 gefoam will occur primarily at the head of the slide and, consequently, the EPS-block gefoam slope system may not include the pavement system. Therefore, Steps 7 and 8 of the full design procedure shown in Figure 14, which involves the pavement system, may not be required and is not part of the modified design procedure shown in Figure 15.

Figure 13 (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) is included in both design procedures shown in Figures 14 and 15 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 shown in Figure 13 (a) is an alternative where the use of EPS blocks would still be the greatest benefit near the crest of the slope above the roadway.



Figure 13. Location of slide mass relative to roadway: (a) slide above roadway and (b) slide below roadway (Hopkins et al. 1988).

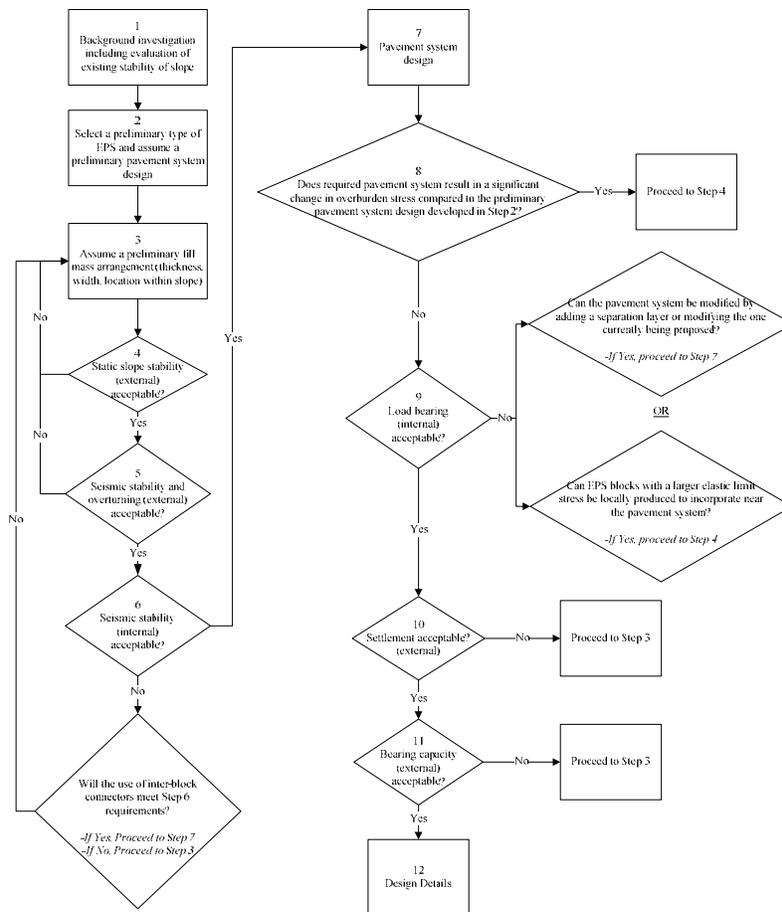


Figure.14. Recommended design procedure for the case of the existing or proposed roadway located within the existing or anticipated slide mass and the existing or anticipated slide mass is located below the roadway, i.e. roadway is near the head of the slide mass.

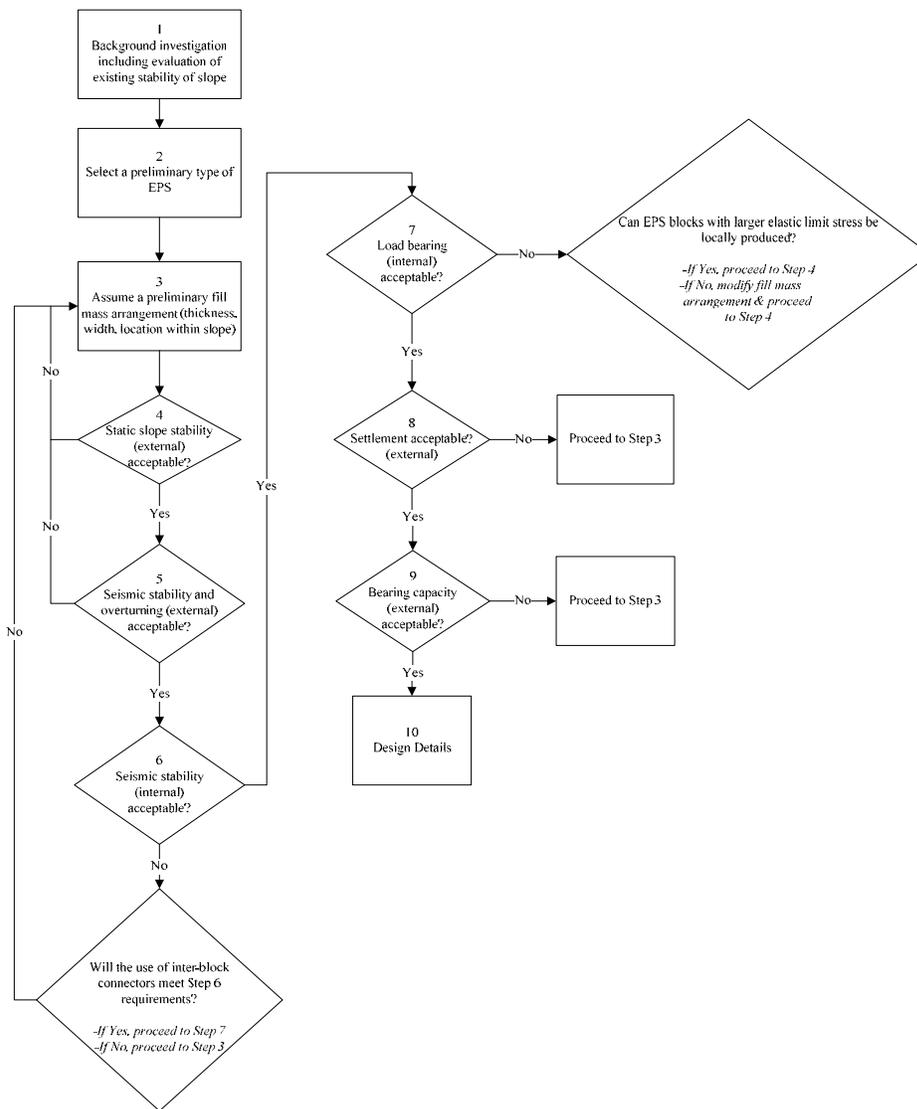


Figure 15. Modified design procedure for the case of the existing or proposed roadway located outside the limits of the existing or anticipated slide mass and/or the existing or anticipated slide mass located above the roadway, i.e. roadway is near the toe of the slide mass.

Figure 16 shows a design selection diagram that can be used to determine whether to use the complete procedure shown in Figure 14 or the modified design procedure shown 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. 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.

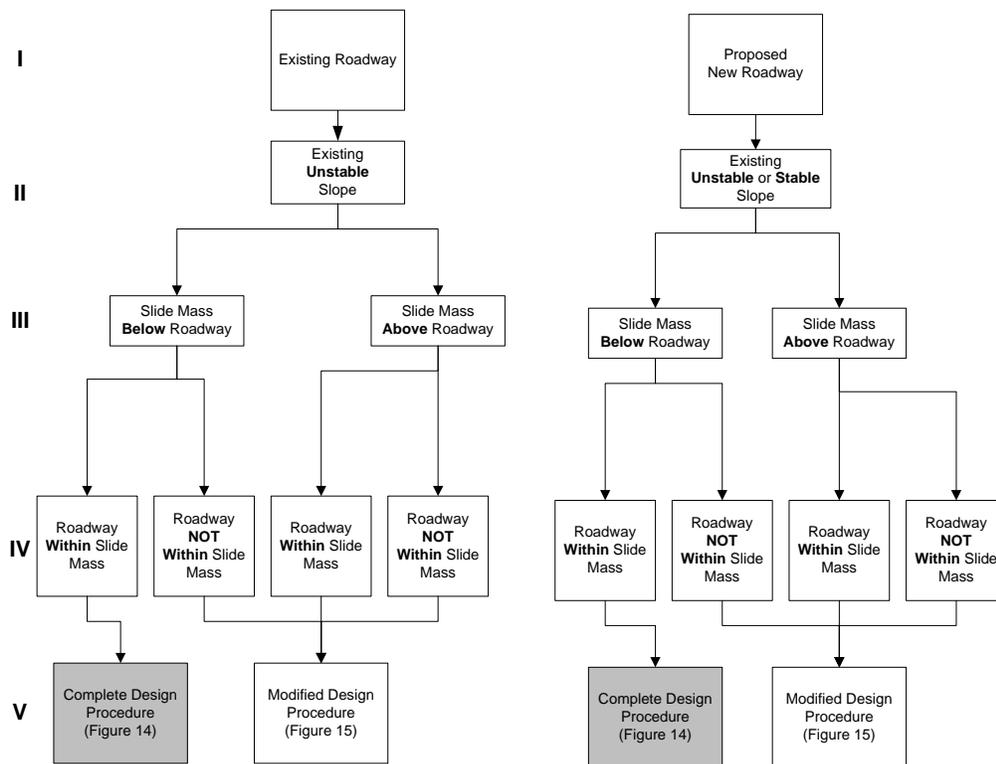


Figure 16. Design procedure selection diagram.

Level V indicates the recommended design procedure that can be used for design. As shown in Figure 16, the complete design procedure shown in Figure 14 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 13 (b), i.e., the roadway is near the head of the slide mass. The modified design procedure shown in Figure 15 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 13 (a), i.e., the roadway is near the toe of the slide mass.

The proposed design procedures shown in Figures 14 through 16 were included in the NCHRP interim report (Arellano et al. 2009a) and were 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 (TRB) held in January 2010. The corresponding TRB paper was included in the meeting compendium of papers. Additionally, TRB accepted the paper for publication in the 2010 Transportation Research Record, Journal of the Transportation Research Board (Arellano et al. 2010).

As part of the effort to simplify the design procedures shown in Figures 14 and 15, the two design algorithms included in these figures were consolidated into a single algorithm as shown in Figure 17. The differences between the two design procedures shown in Figures 14 and 15 are shaded in Figure 17 to facilitate understanding and usage. Therefore, 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 13 (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 13 (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 17 to help differentiate between the complete design procedure shown in Figure 14 that includes Steps 8 and 9 and the modified procedure shown in Figure 15 that does not include Steps 8 and 9.

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 is to use the minimum amount of EPS blocks required to meet stability requirements. Therefore, Steps 3 and 4 that specifically include the optimization of the volume and location of the EPS blocks within the slope were added in the overall design procedure as shown in Figure 17.

In summary, Figure 17 shows the recommended design procedure for EPS-block geofoam slope fills that is included in the NCHRP 24-11(02) preliminary draft final report (Arellano et al. 2011). The following two key revisions were made to the two design algorithms included in Figures 14 and 15. First, the two design algorithms included in Figures 14 and 15 have been consolidated into a single algorithm to facilitate understanding and usage. Second, Steps 3 and 4 were added that specifically include optimization of the volume and location of the EPS blocks within the slope.

SUMMARY

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 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 (guardrails, barriers, median dividers, lighting, signage and utilities).



Figure 17. Complete design procedure for EPS-block geofilm slope fills.

Figure 17 shows the recommended design procedure for EPS-block geofoam slope fills. Procedures to analyze each step in Figure 17 are included in the NCHRP 24-11(02) preliminary draft final report (Arellano et al. 2011). 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 13 (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 13 (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 currently evaluating the mechanical properties of EPS blocks that consist of 100 percent recycled polystyrene beads.

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 3, i.e., existing slope material, fill mass, and pavement system. 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.

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 between 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 17 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.

An example of the extensive use of the NCHRP Project 24-11(01) deliverables related to stand-alone EPS-block geofoam embankments overlying soft ground is the large use of EPS-block geofoam on the Central Artery/Tunnel (CA/T) project in Boston, MA (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 U.S.

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