Framework for Design Guideline for Expanded Polystyrene Block Geofoam in Slope Stabilization and Repair

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

This paper presents the framework for the interim design guideline for the use of expanded polystyrene (EPS) block geofoam for slope stabilization and repair, based on the findings of the 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 design methodology included in the framework is based on an assessment of the existing technology and literature. The Phase II work will refine the interim design guideline framework and address some uncertainties in the current state of the practice of analyzing various failure mechanisms included in the design procedure. The completed research will consist of the following five primary research products: (*a*) a summary of the relevant engineering properties, (*b*) a comprehensive design guideline, (*c*) a material and construction standard, (*d*) economic data, and (*e*) a detailed numerical example. No formal design guidelines on the use of 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.

This paper presents the framework for the interim design guideline for use of expanded polystyrene (EPS) block geofoam for slope stabilization and repair based on the 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.

D. Arellano, Department of Civil Engineering, University of Memphis, 104 Engineering Science Building, Memphis TN 31852-3180. J. B. Tatum, U.S. Army Corps of Engineers, Memphis District, 167 North Main Street, Memphis, TN 38103. T. D. Stark, Department of Civil and Environmental Engineering, University of Illinois at Urbana–Champaign, 205 North Mathews MC-250, Urbana, IL 61801. J. S. Horvath, Department of Civil and Environmental Engineering, Manhattan College, Bronx, NY 10471-4098. D. Leshchinsky, Department of Civil and Environmental Engineering, University of Delaware, 301 DuPont Hall, Newark, DE 19716. Corresponding author: D. Arellano, darellan@memphis.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2170, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 100–108.
DOI: 10.3141/2170-12

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 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 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 sidehill 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 1*a*) or a vertical-sided fill (Figure 1*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 the fill loads on nearby structures.

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 project in Boston, Massachusetts, which was the first major project to use the results of the NCHRP Project 24-11(01) research in practice (*4*). Another project that used the results of Project 24-11(01) is the I-95–Route 1 Interchange (Woodrow Wilson Bridge Replacement) in Alexandria, Virginia. 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 conclude that EPS block geofoam may be a stabilization technology that can be used as an alternative to stability berms to minimize the impacts to environmentally sensitive areas where embankments cross soft or unstable ground conditions (*5*).

As part of FHWA's ongoing Accelerated Construction Technology Transfer Program, it has designated EPS block geofoam as a priority, market-ready technology with a deployment goal that EPS block geofoam will be a routinely used lightweight fill alternative on projects in which the construction schedule is of concern (*6*). FHWA considers EPS block geofoam to be an innovative material for use as part of 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

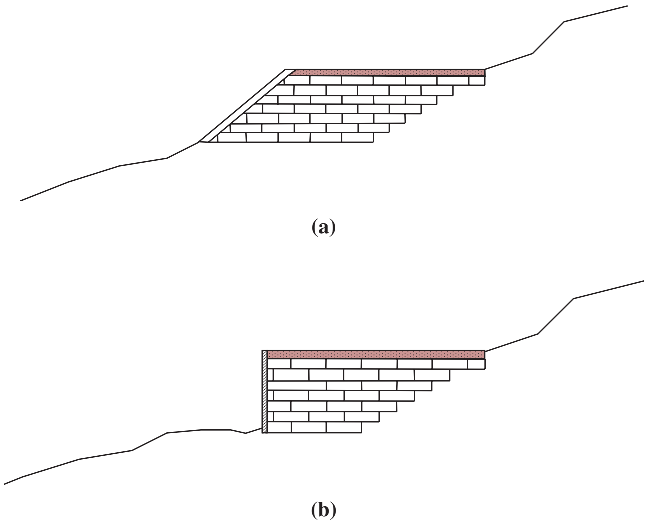


FIGURE 1 Typical EPS block geofoam applications involving sidehill fills: (*a*) slope-sided fill and (*b*) vertical-sided fill (geofoam wall).

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 the growing demand. Therefore, new roadway alignments or widening of existing roadway embankments is or will be required to solve the current and future highway capacity problem. As noted by Spiker and Gori, 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" (*7*). 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 indicate that landslides are among the most widespread geologic hazard on earth and estimate that the damages related to landslides exceed $2 billion annually (*7*).

An additional application of EPS block geofoam for the function of lightweight fill that has not been extensively utilized in the United States but that has been commonly used in Japan is for 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.

Application of the design guideline and the standard included in the Project 24-11(01) reports is limited to stand-alone embankments and bridge approaches over soft ground. The experience in Japan has demonstrated that important analysis and design differences exist 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 a formal and detailed design guideline and appropriate material and construction standard for the 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 here.

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 a slope stabilization and repair design is being implemented, the strategy used by the designer can usually be classified as (*a*) avoid the hazard, (*b*) reduce the driving forces, or (*c*) increase the resisting forces.

The slope stabilization procedure with lightweight fill can be used to reduce the weight of the sliding mass and, thereby, reduce the driving forces of the sliding mass. Use of the lightweight fill materials, especially EPS blocks, may also result in an increase in the resisting forces because the blocks can be stronger than landslide material. The recommended interim design guideline described here 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 for the design of slopes or the remediation of slides by reducing the weight of the slide mass by the use of 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 time frame of the mid-1980s to the mid-1990s, is discussed in various papers, including the *Proceedings of the 1996 International Symposium on EPS Construction Method,* held in Tokyo (*17*). Tsukamoto introduced a design procedure for the use of EPS in slope stabilization (*15*). 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 NCHRP 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 introduced a design procedure, he did not provide guidelines or procedures to perform these steps (*15*). Therefore, one challenge of the Phase I work was to identify potential analysis procedures to perform the design steps.

Because the current state of the practice of slope stability analysis is based on the 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 provides a more detailed discussion of the problems associated with the use of LRFD in slope stability analysis (*18*).

DESIGN PROCEDURE

In the United States, several slope stabilization projects have involved the use of EPS block geofoam, such as US 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 successfully been incorporated into slope stability projects around the world.

These case histories demonstrate that lightweight fill materials can improve slope stability on 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.

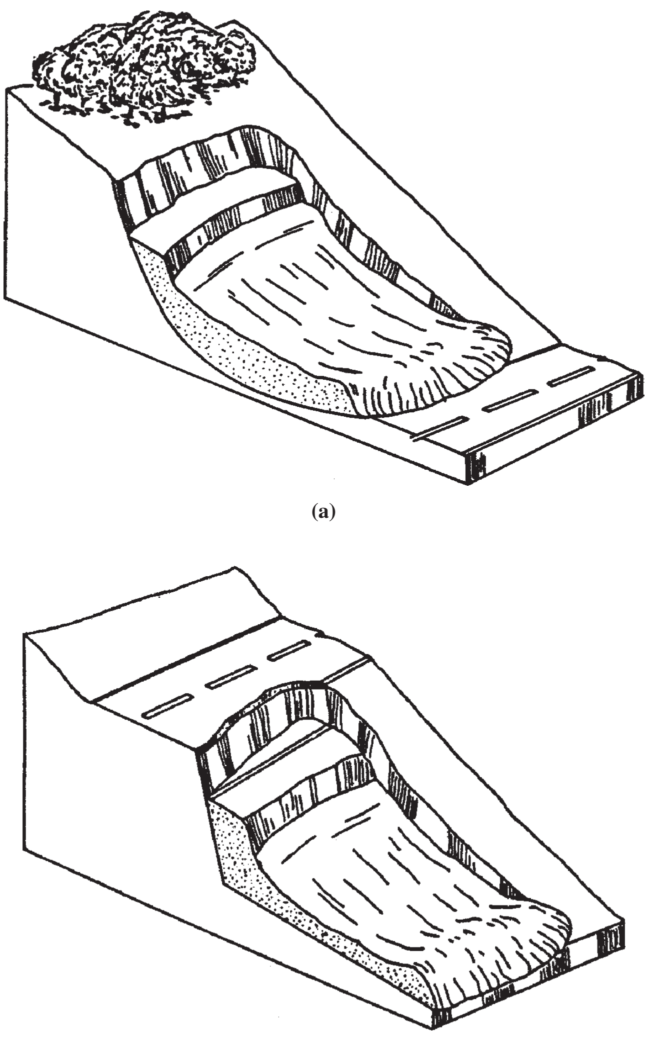
The design requirements of EPS block geofoam slope systems are dependent on the location of the existing or anticipated slip surface in relation to the location of the existing or proposed roadway. Figure 2 shows the two possibilities, which are a slide above the roadway (Figure 2*a*) and a slide below the roadway (Figure 2*b*) that remove some or all of the pavement. Figure 3 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, both of which are shown in Figure 2*b*, that is, 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 or the existing or anticipated slide mass is located above the roadway, or both (as shown in Figure 2*a*), that is, the roadway is near the toe of the slide mass. It should be noted that Figure 2*a* does not imply that EPS blocks can be placed near the toe of the slide, where removal of the existing material and replacement with EPS blocks would contradict the function of lightweight fill, which is to decrease the driving forces that contribute to slope instability, and would instead contribute to further instability. The stabilization of a slide above a roadway scenario shown in Figure 2*a* is an alternative in which the use of EPS blocks near the crest of the slope above the roadway would still provide the greatest benefit.

It is anticipated that the use of EPS block geofoam for the slope application shown in Figure 2*a* 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 primarily occur 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 involve the pavement system, may not be required and are not part of the modified design procedure shown in Figure 4. However, as noted in the design procedures shown in Figures 3 and 4, all designs must include adequate stability analyses to ensure that the proposed location of the EPS blocks will decrease the driving forces and contribute to overall stability. Therefore, Step 4 (static slope stability) is included in both design procedures.

Figure 5 shows a design selection diagram that can be used to determine whether the complete procedure shown in Figure 3 or the modified design procedure shown in Figure 4 should be used. Level I of the decision selection diagram indicates that the proposed design procedure is applicable to both the remedial repair and remediation of existing unstable soil slopes involving existing roadways and the design of planned slopes involving new roadway construction. Level II of the decision selection diagram indicates that for existing roadways the use of EPS block geofoam will typically involve only 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 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 failure of the external stability of the overall EPS block geofoam slope system configuration and failure of the 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 that protects against these three failure modes requires consideration of the interaction between the three



(a)

(b)

FIGURE 2 Location of slide mass relative to roadway: (*a*) slide above roadway and (*b*) slide below roadway (*34*).

FIGURE 3 Recommended design procedure for existing or proposed roadway located within existing or anticipated slide mass and when existing or anticipated slide mass is located below roadway; that is, roadway is near head of slide mass.

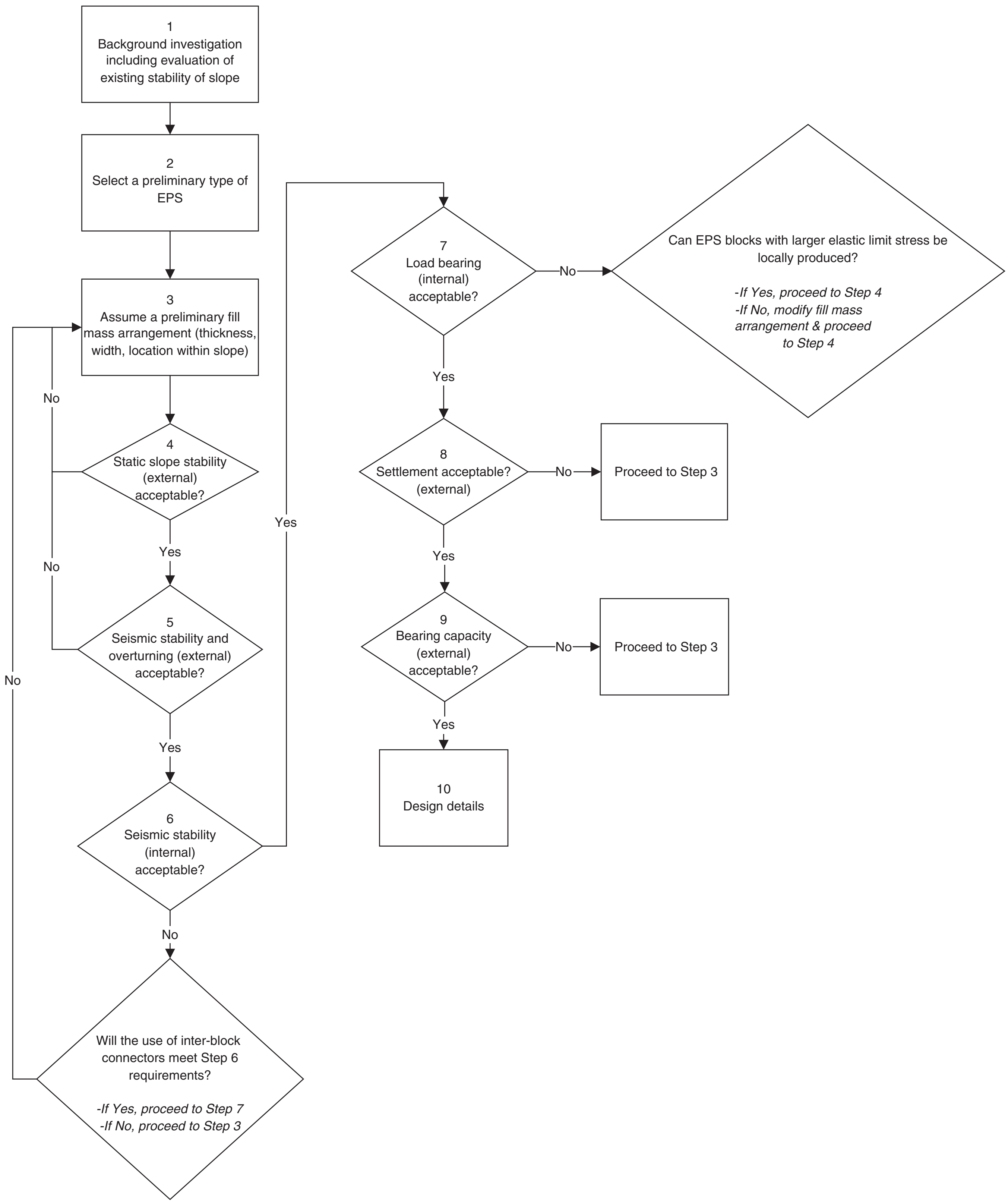


FIGURE 4 Modified design selection procedure for existing or proposed roadway located outside limits of existing or anticipated slide mass, when existing or anticipated slide mass is located above roadway, or both; that is, roadway is near toe of slide mass.

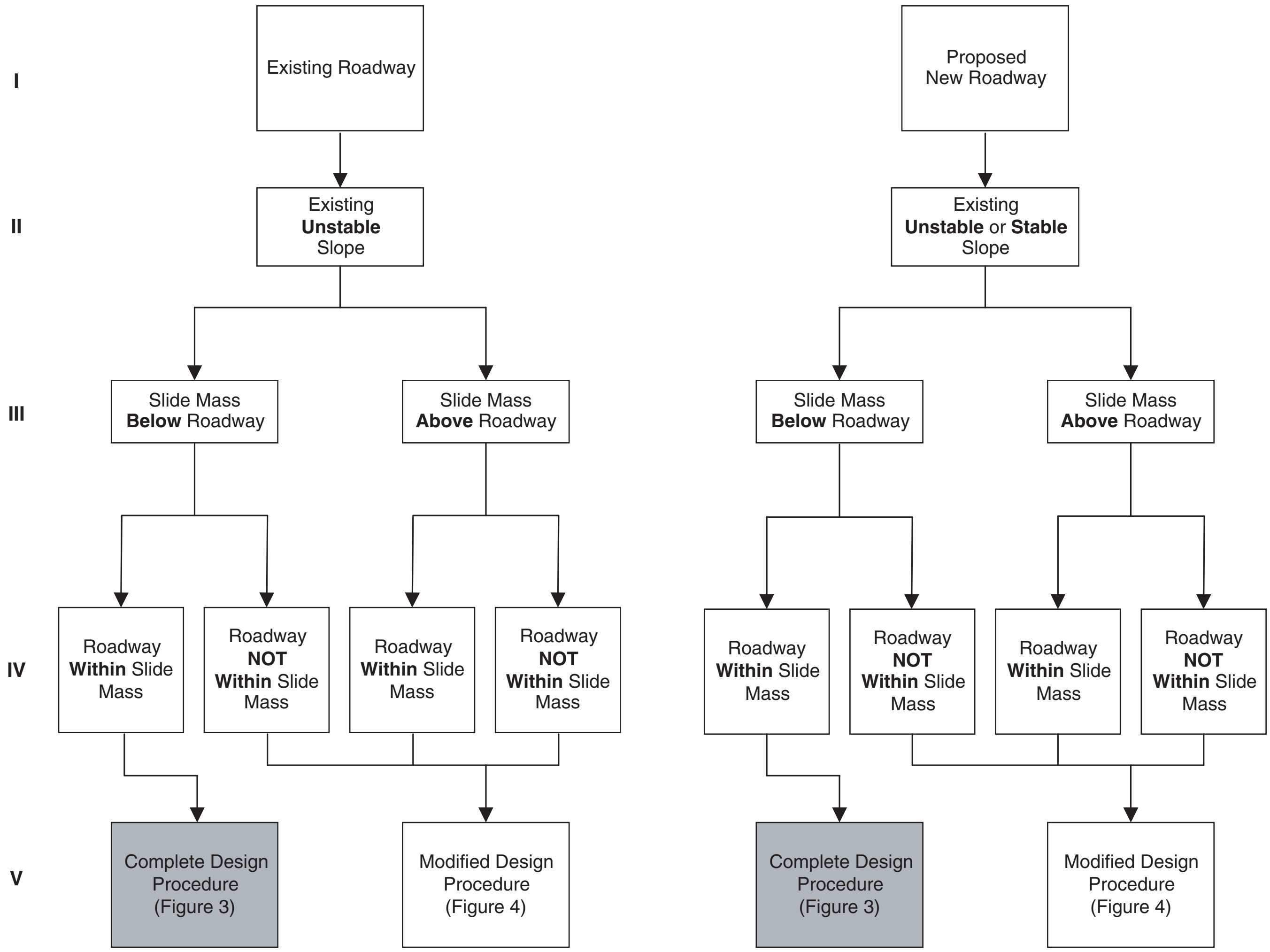


FIGURE 5 Design selection procedure diagram.

major components of an EPS block slope system shown in Figure 6, that is, the existing slope material, fill mass, and pavement system. The subsequent sections include an overview of these three failure modes.

External Instability Failure Mode

The design for the 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 the overlying pavement system interact with the existing slope material.

The external stability failure mechanisms included in the NCHRP 24-11(01) design procedure for stand-alone embankments consist of those related to the bearing capacity of the foundation material, static and seismic slope stability, hydrostatic uplift (flotation), translation and overturning because of water (hydrostatic sliding), translation and overturning because of wind, and settlement failure. 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 NCHRP 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, on the basis of 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, analyses for the hydrostatic uplift (flotation) and translation because of water failure mechanisms that are included in the NCHRP 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. The final drainage system configuration should be checked to ensure that positive drainage is maintained throughout the slope. In addition to a permanent drainage system, temporary dewatering and drainage systems may need to be considered for construction.

Translation and overturning because of wind is a failure mechanism that is considered in the NCHRP 24-11(01) design of stand-alone

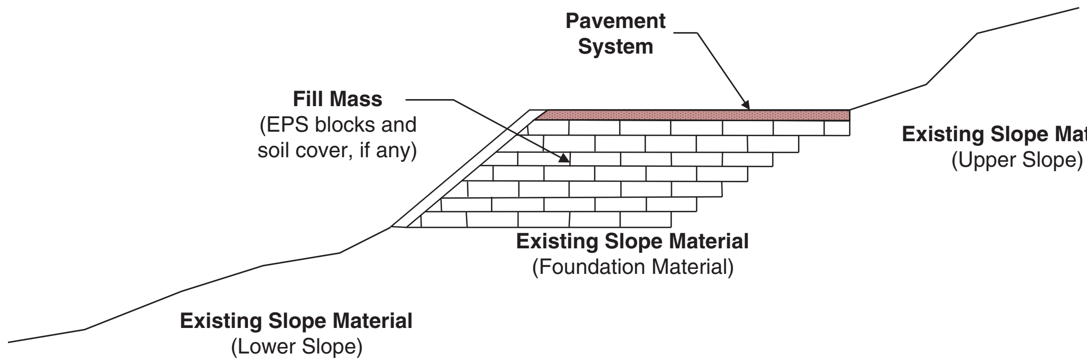


FIGURE 6 Major components of an EPS block geofoam slope system.

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 based on available wind pressure data for structures located on slopes be performed 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 or through both the fill mass and existing slope material, horizontal sliding of the entire EPS block geofoam fill mass, overturning of a vertical-sided embankment, failure of the bearing capacity of the existing foundation material because of seismic loading 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, limitation of the impact on underlying 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

The internal instability failure mechanisms included in the NCHRP 24-11(01) design procedure for stand-alone embankments consist of translation because of water and wind, seismic stability, and load bearing. As indicated earlier in the discussion of the external instability failure mode, translation because of 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 NCHRP 24-11(01) design procedure for stand-alone embankments because little or no static driving force is 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, whereas 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 or between the pavement system and the upper level of blocks because of 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 resist directly the 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 the geofoam embankment will behave as a single, coherent mass when it is 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 interlocking. The interim standard in the interim report provides block placement guidelines that should provide adequate interlocking in the vertical direction (*1*). Therefore, the primary seismic internal stability issue is the potential for horizontal sliding along the horizontal interfaces between blocks 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 project (*38–40*) is load-bearing failure because of seismic rocking of the fill mass, which contributes to an increase in the vertical normal stress within the EPS block fill mass. Phase II of the NCHRP Project 24-1(02) research will include evaluation of the applicability of this seismic shaking failure mechanism for slopes.

Load-bearing failure of the EPS blocks because of excessive dead or gravity loads from the overlying pavement system and traffic loads is the second 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, which 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.

A separation layer such as a concrete slab or a hydrocarbon-resistant geomembrane between the top of the EPS blocks and the overlying pavement system is sometimes required to protect the EPS blocks from excessive traffic loads and fuel spills, respectively. Details about separation materials are included in the NCHRP Project 24-11(01) report (*3*).

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

Pavement System Failure Mode

The 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 some similar criterion. Also, when the pavement cross-section is designed, some consideration should be given to providing sufficient support, by either 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 NCHRP Project 24-11(01) reports for stand-alone embankments. However, the Phase II research for slope applications will consist of updating the NCHRP 24-11(01) pavement design recommendations so that the updated recommended pavement design procedures are in alignment with those in the current AASHTO *Mechanistic–Empirical Pavement Design Guide* (*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, that is, external instability, internal instability, and pavement system failure. Because of this interaction, the design procedure involves interconnected analyses of the three components. For example, some issues of pavement system design act opposite some of the design issues involving the 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 the 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 an EPS block with the lowest possible density. Therefore, the proposed design procedure will produce a cost-efficient design.

SUMMARY

This paper presents the framework for the interim design methodology from the NCHRP Project 24-11(02) interim report for the use of geofoam for slope stabilization (*1*). 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 or the existing or anticipated slide mass is located above the roadway, as shown in Figure 2*a.*

The recommended interim design methodology is based on an assessment of the existing technology and literature. The Phase II work will refine the interim design guideline and address some uncertainties in the current state of the practice of analyzing various failure mechanisms included in the design procedure. The completed research will consist of the following five primary research products: (*a*) a summary of relevant engineering properties, (*b*) a comprehensive design guideline, (*c*) a recommended material and construction standard, (*d*) economic data, and (*e*) a detailed numerical example. Completion of Phase II is scheduled for June 2010. A current summary of the engineering properties of EPS blocks for the function of lightweight fill is available in the NCHRP Project 24-11(01) report (*3*).

Currently, no formal design guidelines on the 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 that can provide a safe and economical solution for slope stabilization and repair.

ACKNOWLEDGMENT

The authors acknowledge the support provided by NCHRP under Project NCHRP 24-11(02), Guidelines for Geofoam Applications in Slope Stability Projects.

REFERENCES

1. Arellano, D., T. D. Stark, J. S. Horvath, and D. Leshchinsky. *Guidelines for Geofoam Applications in Slope Stability Projects.* NCHRP Project 24-11(02) Interim Report. Transportation Research Board of the National Academies, Washington, D.C., 2009.

2. Stark, T. D., D. Arellano, J. S. Horvath, and D. Leshchinsky. *Guideline and Recommended Standard for Geofoam Applications in Highway Embankments.* NCHRP Project 24-11 Report. Transportation Research Board of the National Academies, Washington, D.C., 2004. http://trb.org/publications/nchrp/nchrp_rpt_529.pdf. Accessed Dec. 2008.
3. Stark, T. D., D. Arellano, J. S. Horvath, and D. Leshchinsky. *Geofoam Applications in the Design and Construction of Highway Embankments.* NCHRP Web Document 65 (Project 24-11). Transportation Research Board of the National Academies, Washington, D.C., 2004. http://trb.org/publications/nchrp/nchrp_w65.pdf. Accessed Dec. 2008.
4. Riad, H. L. EPS Structures Innovations on Central Artery/Tunnel (CA/T) Project. Presented at BSCES/ASCE Geo-Institute Seminar on Recent Advances in Geotechnical Engineering, Waltham, Mass., 2005. http://jshce.com/files/RIAD_BSCES_EPS_Structures_on_CA-T_Project.pdf. Accessed Dec. 2008.
5. Thompson, M. J., and D. J. White. *Review of Stability Berm Alternatives for Environmentally Sensitive Areas.* Final Report, Iowa DOT Project CSMR(5)-90-0, CTRE Project 05-203. Center for Transportation Research and Education, Iowa State University, Ames, 2005.
6. *Priority, Market-Ready Technologies and Innovations List: Expanded Polystyrene (EPS) Geofoam.* Publication FHWA-HRT-06-061. FHWA, U.S. Department of Transportation, 2006. http://www.fhwa.dot.gov/crt/lifecycle/geofoam.pdf. Assessed Dec. 2008.
7. Spiker, E. C., and P. L. Gori. *National Landslide Hazards Mitigation Strategy—A Framework for Loss Reduction.* USGS Circular 1244. U.S. Geological Survey, Reston, Va., 2003.
8. *Special Report 247: Landslides: Investigation and Mitigation* (A. K. Turner and R. L. Schuster, eds.), TRB, National Research Council, Washington, D.C., 1996.
9. Abramson, L. W., T. S. Lee, S. Sharma, and G. M. Boyce. *Slope Stability and Stabilization Methods,* 2nd ed. John Wiley and Sons, Inc., New York, 2002.
10. Cornforth, D. H. *Landslides in Practice: Investigation, Analysis, and Remedial/Preventative Options in Soils.* John Wiley and Sons, Inc., Hoboken, N.J., 2005.
11. Duncan, J. M., and S. G. Wright. *Soil Strength and Slope Stability.* John Wiley and Sons, Inc., Hoboken, N.J., 2005.
12. Holtz, R. D. *NCHRP Synthesis of Highway Practice 147: Treatment of Problem Foundations for Highway Embankments.* TRB, National Research Council, Washington, D.C., 1989.
13. Horvath, J. S. *Geofoam Geosynthetic.* Horvath Engineering, P.C., Scarsdale, N.Y., 1995.
14. Negussey, D. *Slope Stabilization with Geofoam.* FHWA Research Project 2398P62000015. Geofoam Research Center, Syracuse University, Syracuse, N.Y., 2002.
15. Tsukamoto, H. Slope Stabilization by the EPS Method and Its Applications. *Proc., International Symposium on EPS Construction Method (EPS Tokyo '96).* EPS Construction Method Development Organization, Tokyo, 1996, pp. 362–380.
16. Lee, K.-M., G. Zhu, D. K. W. Tang, B. K. W. Cheng, and C. L. Y. Yip. A New LGM for Construction of Embankments, Fill Slopes and Retaining Walls. *Proc., International Workshop on Lightweight Geo-Materials (IW-LGM2002): A New Horizon in Soil and Ground Improvement.* Japanese Geotechnical Society, Tokyo, 2002, pp. 253–260.
17. *Proc., International Symposium on EPS Construction Method (EPS Tokyo'96).* EPS Construction Method Development Organization, Tokyo, 1996.
18. Leshchinsky, D. LRFD in MSE Walls: Adopt or Ignore? Presented at 16th GSI/GRI Conference, Philadelphia, Pa., 2002.
19. Yeh, S.-T., and J. B. Gilmore. Application of EPS for Slide Correction. In *Stability and Performance of Slopes and Embankments-II, Geotechnical Special Publication 31* (R. B. Seed and R. W. Boulanger, eds.), ASCE, New York, 1992.
20. Jutkofsky, W. S. *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, 1998.
21. Jutkofsky, W. S., J. T. Sung, and D. Negussey. Stabilization of an Embankment Slope with Geofoam. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1736,* TRB, National Research Council, Washington, D.C., 2000, pp. 94–102.
22. Reuter, G., and J. Rutz. A Lightweight Solution for Landslide Stabilization. *Geotechnical Fabrics Report,* Vol. 18, No. 7, 2000, pp. 42–43.
23. Reuter, G. R. Use of Geofoam for Landslide Stabilization-CTH "A," Bayfield County, Wisconsin. *Proc., 3rd International Geofoam Conference,* Salt Lake City, Utah, 2001.
24. Alabama Department of Transportation. *Slide Correction on AL 44 at MP 6.4, Marion County.* Foundation Report ER-6147(4). Alabama Department of Transportation, Montgomery, 2004.
25. Stark, T. D., and G. Mann. Landslide Stabilization Using Geofoam. *Proc., 8th International Conference on Geosynthetics,* Yokohama, Japan, 2006.
26. Read, J., T. Dodson, and J. Thomas. *Experimental Project Use of Shredded Tires for Lightweight Fill.* Postconstruction report. Oregon Department of Transportation, Salem, 1991.
27. Coulter, T. S. Woodwaste as Lightweight Fill in Highway Construction. *Proc., 28th Conference of Western Association of Canadian Highway Officials,* Winnipeg, Manitoba, Canada, 1975.
28. Kilian, A. P. Use of Sawdust in Landslide Correction and Settlement Control. In *35th Annual Road Builders Proceedings,* 1984, pp. 35–48.
29. Nelson, D. S., and W. L. Allen. Sawdust as Lightweight Fill Material. *Highway Focus,* Vol. 6, No. 3, 1974, pp. 53–66.
30. Nelson, D. S., and W. L. Allen. *Sawdust as a Lightweight Fill Material.* Report FHWA-RD-74-502. FHWA, U.S. Department of Transportation, 1974.
31. *Matériaux Légers pour Remblais/Lightweight Filling Materials.* Permanent International Association of Road Congresses—World Road Association, La Defense, France, 1997.
32. Peterson, D. R., A. D. Zander, R. J. Swint, K. G. Buss, and R. A. Nichols. Slide Area Stabilization with Sawdust and Bark Chips. *The Transactions of the American Society of Agricultural Engineers,* Vol. 24, No. 4, 1981, pp. 970–976.
33. Sharma, S., and T. Buu. The Bud Peck Slide, I-15, Near Malad, Idaho. In *Transportation Research Record 1343,* TRB, National Research Council, Washington, D.C., 1992, pp. 123–129.
34. Hopkins, T. C., D. L. Allen, R. C. Deen, and C. G. Grayson. *Slope Maintenance and Slide Restoration: Participant Manual.* FHWA Report RT-88-040. University of Kentucky Transportation Center, Lexington, 1988.
35. Lazarte, C. A., V. Elias, R. D. Espinoza, and P. J. Sabatini. *Geotechnical Engineering Circular No. 7: Soil Nail Walls.* Publication FHWA 0-IF-03-017. FHWA, U.S. Department of Transportation, 2003.
36. Elias, V., B. R. Christopher, and R. R. Berg. *Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design & Construction Guidelines.* Publication FHWA-NHI-00-043. National Highway Institute, Washington, D.C., 2001.
37. Byrne, R. J., D. Cotton, J. Porterfield, C. Wolschlag, and G. Ueblacker. *Manual for Design and Construction Monitoring of Soil Nail Walls.* Publication FHWA-SA-96-069R. FHWA, U.S. Department of Transportation, 1998.
38. Horvath, J. S. Lessons Learned from Failure: EPS Geofoam. *Geotechnical Fabrics Report,* Oct./Nov., 2004, pp. 34–37.
39. Riad, H. L. EPS Structures Innovations on Central Artery/Tunnel (CA/T) Project. Presented at BSCES/ASCE Geo-Institute Seminar on Recent Advances in Geotechnical Engineering, Waltham, Mass., 2005. http://jshce.com/files/RIAD_BSCES_EPS_Structures_on_CA-T_Project.pdf. Accessed Dec. 2008.
40. Riad, H. L., and J. S. Horvath. 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., 2004, pp. 2028–2037.
41. Arellano, D., and T. D. Stark. Load Bearing Analysis of EPS-Block Geofoam Embankments. *Proc., 8th International Conference on the Bearing Capacity of Roads, Railways and Airfields,* Vol. 2 (E. Tutumluer and I. L. Al-Qadi, eds.), CRC Press/Balkema, Leiden, Netherlands, 2009, pp. 981–990.
42. *Mechanistic–Empirical Pavement Design Guide: A Manual of Practice.* Interim Edition. AASHTO, Washington, D.C., 2008.

The findings, conclusions, or recommendations either inferred or specifically expressed in this document do not necessarily indicate acceptance by the National Academy of Sciences, FHWA, or AASHTO.

The Transportation Earthworks Committee peer-reviewed this paper.