Preferred Design Procedure

The Federal Highway Administration (FHWA) and National Cooperative Highway Research Program (NCHRP) have two documents for this technology that contain design guidance information. They are:

<table>
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<th>Publication Title</th>
<th>Publication Year</th>
<th>Publication Number</th>
<th>Available for Download</th>
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<tr>
<td>Ground Improvement Methods - Volume I</td>
<td>2006</td>
<td>FHWA NHI-06-019</td>
<td>No¹</td>
</tr>
<tr>
<td>(Elias et al. 2006)</td>
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<tr>
<td>Geofoam Applications in the Design and Construction of Highway Embankments (Stark et al. 2004b)</td>
<td>2004</td>
<td>NCHRP Web Document 65</td>
<td>Yes²</td>
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¹ [http://www nhi fhwa dot gov/training/nhistore aspx](http://www.nhi.fhwa.dot.gov/training/nhistore.aspx)

Summary of Design/Analysis Procedure: General Design Guidance

Current FHWA Reference(s): *Elias et al. (2006)*

Supporting Reference(s): *Christopher et al. (2006)*
*NYSDOT (2008)*

Lightweight fills have been used in the geotechnical design of highway embankments to reduce the possibility of ultimate and serviceability failures. Ultimate failures are generally described as the total collapse of the embankment. This failure mode is associated with the strength of the materials in the foundation and embankment, and it can result from bearing capacity failure of the soil beneath the embankment or slope stability failure through the embankment and the foundation. The use of lightweight fills rather than standard fill material can reduce the load on the underlying soils, thus increasing the factor of safety against ultimate failure. Serviceability failures can generally be described as settlement or movements of the surface, i.e., excessive total settlements, rutting, or differential settlements that would deem the embankment unusable. Serviceability failures are generally associated with compression of the foundation or embankment materials. Because lightweight fills reduce the load on the foundation soils, they reduce settlements.

For design and construction purposes, lightweight fills can generally be grouped into two categories: materials that behave and have properties similar to granular soils, and materials that
have an unconfined compressive strength and behave similarly to cohesive soils in undrained loading (Elias et al. 2006).

Granular lightweight fill materials include:

- Wood fiber.
- Blast furnace slag.
- Boiler slag.
- Fly ash.
- Expanded Shale, Clay & Slate (ESCS).
- Shredded tires.

Lightweight fill materials with an unconfined compressive strength include:

- Geofoam.
- Cellular concrete.

The same design procedures used for conventional fills can be used for granular lightweight fill materials with additional considerations dependent on the specific lightweight material. These additional considerations may include evaluation of the durability, water absorption potential, corrosion potential, combustion potential, erosion potential, and environmental impacts. Elias et al. (2006) provides a list of environmental, design, and construction considerations for each of the specific granular lightweight fill materials, as well as summaries of their design parameters. For tire shred embankments, NYSDOT (2008) provides a useful summary of design guidelines that address post-construction compression, separation of tire shreds from surrounding soil, and fill geometry to prevent spontaneous combustion.

Design procedures for lightweight fill materials with unconfined compressive strength are unique to the specific material. For Expanded PolyStyrene (EPS) geofoam, the design procedure is divided into three main categories: pavement design, internal stability, and external stability. Each of these is discussed in detail in the NCHRP Geofoam Design Procedure summary below. Elias et al. (2006) provides a table of average properties for geofoam and cellular concrete as well as a list of specific design and construction considerations.

The pavement design procedure for all lightweight fill types is best summarized by the following excerpt from FHWA NHI-05-037: Geotechnical Aspects of Pavements (Christopher et al. 2006):

“With regard to pavement design, if a minimum of 1 m (3 ft) of good quality gravel type fill is placed between the pavement structure and the lightweight materials as a cover, then the lightweight material will have little impact on pavement design, even for the more compressible tire and geofoam materials.”
However, if a thinner cover must be used, the support value for these materials must be determined. Lab tests can be used, as discussed in Chapter 5, especially for the granular type materials. The ideal method is to perform field resilient modulus tests on placed material (i.e., on cover soils after placement over the lightweight material(s)), especially for the bulkier materials, such as tires and geofoam.”

Summary of Design/Analysis Procedure: NCHRP Geofoam Design Procedure

Current NCHRP Reference(s): Stark et al. (2004a, b)
Supporting Reference(s): Zornberg et al. (2005)

The Transportation Research Board (TRB) National Cooperative Highway Research Program (NCHRP) completed research on NCHRP Project 24-11: Guidelines for Geofoam Applications in Embankment Projects in 2004. Findings were published as NCHRP Report 529, Guideline and Recommended Standard for Geofoam Applications in Highway Embankments, and released online as NCHRP Web Document 65, Geofoam Applications in the Design and Construction of Highway Embankments (Stark et al. 2004a and Stark et al. 2004b). Report 529 consists of only the recommended design guidelines and standards. Web Document 65 consists of the entire report and appendices (including the guidelines and standards from Report 529 as Appendices B & C). Henceforth, the complete report from NCHRP Project 24-11, Web Document 65, will be referred to as NCHRP 24-11.

The NCHRP 24-11 report provides a step-by-step procedure for designing highway embankments using geofoam, which is another name for EPS blocks. The charts provided throughout the document are developed specifically for EPS blocks and cannot be applied to other types of lightweight fills. However, the general design issues and approaches are very similar for some other categories of lightweight fills, e.g., tire bales (Zornberg et al. 2005). The following paragraphs provide a descriptive summary of the design procedure in the NCHRP 24-11 report.

There are three main categories of design: pavement design, external stability, and internal stability. The pavement design criteria are intended to prevent rutting, cracking, or similar pavement issues. External stability refers to how the fill mass and pavement affect the soil below. Internal stability refers to the ability of the fill mass to support itself and the pavement. Specific failure modes classified within each of these categories are discussed in subsequent paragraphs. Altering the design of the embankment to increase the factor of safety in one aspect of design can often decrease the factor of safety in another aspect. For example, the use of a denser geofoam will be beneficial to the internal stability against translation, but will decrease
the external stability against bearing capacity as a result of increased load. Consequently, design of lightweight fill embankments is an iterative process.

The design of pavement above lightweight fill is similar to standard pavement design procedures once equivalent properties have been assigned to the fill. Research has been conducted on the resilient modulus of different grades of geofoam, and the results are presented in the NCHRP 24-11 document. The intent of the pavement design procedure is to provide the most economical thickness and arrangement of pavement materials while providing sufficient factors of safety against cracking and rutting. It should be noted that a minimum pavement system thickness of 24 inches above the geofoam is recommended to minimize the potential for differential icing and solar heating. The pavement can be designed as an asphalt pavement, a concrete pavement, or a combination of the two. A concrete pavement system itself is generally more expensive than asphalt, but concrete more effectively dissipates the traffic loads applied to the geofoam fill, and it can allow for the use of a lighter geofoam, thus reducing costs.

For flexible pavement design, a comprehensive design procedure is provided in the NCHRP 24-11 document. A design catalog for low volume roads\(^1\) is included that can be used to obtain the structural number based on the EPS type, reliability level, and traffic level. After obtaining the structural number, the AASHTO Guide for Design of Pavement Structures or state DOT design manuals can be used to select layer coefficients and determine the most economical pavement system. The procedure also includes a table of minimum recommended ASSHTO values for the thickness of the asphalt concrete and aggregate base based on traffic Equivalent Single-Axle Loads (ESALs).

Likewise, for rigid pavement design, a comprehensive design procedure is provided in the NCHRP 24-11 document. A set of design catalogs is used to obtain the rigid concrete thickness based on the EPS type, reliability level, ESALs, modulus of rupture, and whether or not edge support and/or a load transfer device is included in the design. The design catalogs are based on the same assumptions and general procedure as those from the AASHTO Guide for Design of Pavement Structures.

For preliminary estimation of the dead load imposed by the pavement system, a thickness of 24 inches and unit weight of 130 pcf should be used, according to the NCHRP 24-11 report.

External stability is broken into the following categories in the NCHRP 24-11 report: global total and differential settlement, bearing capacity, slope stability, seismic stability, hydrostatic uplift, hydrostatic sliding and overturning, and translation and overturning due to wind.

Global embankment settlement is a sum of the following: immediate distortion and compression of the fill mass, immediate distortion and settlement of the foundation soil, primary consolidation

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\(^1\) From NCHRP 24-11, “Even though the [pavement] design catalogs… are for low-volume roads, EPS-block geofoam can be and has been used for high-volume traffic roads, such as interstate highways.”
of the foundation soil, secondary consolidation of the foundation soil, and long-term creep of the geofoam. Immediate distortion and compression of the fill mass and foundation soils occur during the construction of the embankment, and they generally do not create any serviceability failures. Primary consolidation occurs as a result of the dissipation of increased pore pressures in response to the applied total stresses. Primary consolidation can be calculated using standard consolidation settlement methods. Secondary consolidation occurs after all pore pressures have been dissipated. Creep of the geofoam is generally neglected because it accounts for only 1% of the total settlement over a 50-year period when the geofoam is selected based on the NCHRP 24-11 design procedure. The consolidation characteristics of the foundation soils can be obtained through laboratory testing of undisturbed samples. According to NCHRP 24-11, acceptable post-construction settlements for transportation embankments are generally 0.3 to 0.6 meters (1 to 2 feet), provided that the settlements are uniform, occur slowly during the life of the roadway, and are not adjacent to pile supported structures. The transition zone between geofoam and embankment soil should be gradual to minimize differential settlement. The calculated settlement gradient within the transition zone should not exceed 1:200 (vertical:horizontal).

Global bearing capacity refers to the ability of the foundation soil to carry the load of the embankment. The bearing capacity evaluation is a standard soil bearing capacity calculation using Prandtl’s equation, which is often used to calculate the bearing capacity of footings. Some simplifications of Prandtl’s equation are made based on the following two assumptions: (1) the embankment will be constructed on a soft, cohesive soil foundation so that undrained strengths will control the critical failures, and (2) the embankment will be constructed from the existing ground surface and upward, thus the depth-of-footing parameter is zero. The applied loads include the vertical stress from the embankment soil, pavement, and traffic surcharge. A factor of safety of 3.0 is recommended for the design of global bearing capacity.

A global slope stability failure could result in excessive settlement of the entire embankment and may be observed in conjunction with noticeable heaving of the ground surface at some distance from the side of the embankment. The factor of safety for slope stability can be determined by using the general design charts provided in NCHRP 24-11 or performing a project specific slope stability analysis. General design charts have been developed for embankments with different geometries (side slopes, heights, and number of lanes) and with varying undrained shear strengths of the foundation soils. Project specific slope stability analyses should be conducted using a slope stability method that satisfies all conditions of equilibrium, e.g., Spencer’s method, and with modified strength parameters for the geofoam. It is assumed that failure will occur through the system of geofoam blocks and that the failure surface through the embankment would consist of 25% shearing through intact EPS blocks and 75% shearing along joints between the blocks. Therefore, the representative cohesion value for the global shear strength of the geofoam is estimated to be one-quarter of the cohesive strength of the geofoam. In addition, the cohesion value needs to be corrected for strain incompatibility between the soft foundation soil
and the EPS-block geofoam. This procedure for characterizing the geofoam strength is used for both external and internal slope stability analyses. Additional information regarding slope stability analysis for geofoam embankments is provided in the NCHRP 24-11 report. As for global bearing capacity, the undrained condition will be critical during construction of the embankment. NCHRP 24-11 recommends that a factor of safety of 1.5 against global slope stability failure should be used for design.

The global seismic stability analysis is closely related to the static slope stability analysis. A critical failure surface is first determined for the static case. The shear strength along the critical static failure plane is then reduced by 20% for cohesive soils and 80 to 90% for liquefiable soils to account for strength loss due to earthquake shaking. No reduction is applied for cohesionless, non-liquefiable soils. An appropriate horizontal seismic coefficient is applied at the center of gravity of the portion of the embankment within the sliding surface, and the pseudo-static slope stability factor of safety is calculated. Because the seismic motion will be a temporary condition, a factor of safety of 1.2 is deemed sufficient for design. As with the global slope stability analysis, charts have been developed and presented in NCHRP 24-11 for various geometries, undrained shear strengths, and seismic coefficients. One beneficial characteristic of EPS blocks is that the embankment can be constructed vertically. In the case of a vertical walled, rectangular embankment, as opposed to a trapezoidal embankment with inclined side slopes, the seismic analysis should also consider overturning at the toe of the embankment. The factor of safety against overturning is calculated by dividing the sum of the stabilizing moments by the sum of the overturning moments. Again, a factor of safety of 1.2 is deemed sufficient for design because the seismic motion will be a temporary condition.

Designing for hydrostatic sliding may be necessary because the geofoam material can weigh as little as 1% of the weight of standard fill materials. If the water level is temporarily raised along the sides of the embankment during flood conditions, the embankment could potentially be lifted due to hydrostatic pressures developed at the interface of the embankment and the foundation soil. To counteract the hydrostatic uplift, the weight of the pavement plus the weight of the embankment soil should be great enough to provide a factor of safety of 1.2 against the uplift pressures.

If a differential water level develops from one side of the embankment to the other, the resultant horizontal hydrostatic force could cause the embankment to slide perpendicular to the direction of the roadway. Should this condition occur, the shear strength at the base of the embankment would be reduced as a result of the lowered effective stress at the embankment-foundation soil interface due to the uplift pressures developed by the raised water levels. The resulting resisting shear strength (the effective normal force multiplied by the tangent of the interface friction angle, \( \delta \), at the embankment-foundation soil contact) should be greater than the driving lateral hydrostatic forces by a factor of 1.2 to protect against displacement due to hydrostatic translation. For tall and narrow embankments, the differential water levels can also act to
overturn the embankment. To design against overturning, the stabilizing moments about the toe of the embankment (the weight of the embankment and pavement multiplied by half of the width) should be greater than the driving moments (the net lateral water force multiplied by the height above the base where the net lateral water force acts) by a factor of 1.2.

Internal stability issues address the interaction between elements at each interface, i.e., the interfaces between EPS blocks and the interface between the pavement and the underlying EPS block. Internal stability is divided into the following categories: translation due to hydrostatic sliding, translation due to wind, seismic stability, and load bearing.

Internal design against lateral translation is similar to the global design methods, but the failure surfaces are considered at the block-to-block and pavement-to-block interfaces. As discussed above for global translation of the entire embankment due to differential water pressures, individual blocks or groups of blocks within the embankment could be displaced laterally. To counteract these forces, the overburden pressure associated with the weight of the pavement and soil above each block-to-block interface must be adequate to provide enough effective normal stress and shear strength to counteract the lateral water pressures. A factor of safety of 1.2 is considered adequate for internal hydrostatic sliding because the raised water level is a temporary condition.

The same type of pseudo-static analysis as used for the global seismic analysis is also used for the internal seismic analysis. However, each interface, including block-to-block and pavement-to-block interfaces, is analyzed separately. The suggested design factor of safety against internal seismic failure is 1.2.

Designing against internal bearing capacity ensures that the EPS blocks do not deflect under loading to an extent that excessive settlement occurs at the road surface. The approach consists of determining the effective vertical stress at the surface of each geofoam block and calculating the deflection based on the properties of the geofoam block. In general, the critical contact for internal bearing capacity is the contact between the pavement system and the top layer of geofoam fill. As a result, in certain situations, it can be cost effective to add a concrete separation slab beneath the pavement to dissipate the traffic loads using a load spread approach with a 1:1 (horizontal:vertical) rate.

There are no documented cases of an embankment failing as a result of wind loads. However, it is still recommended that the embankments be designed against translation due to wind if it is expected that the embankment will be exposed to hurricane force winds. The global and internal design procedures for translation due to wind are similar to translation due to differential water pressures, except that the wind forces driving potential translation are determined from NCHRP 24-11. Tall and narrow embankments subject to hurricane winds should be designed against global overturning as well. Again, because the hurricane winds would be a temporary condition, an adequate factor of safety against translation and overturning due to wind is assumed to be 1.2.
Each of these failure modes must be satisfied by the appropriate factors of safety or settlement criteria. The design process is iterative because changing one element of the embankment design will increase some factors of safety while decreasing others. The NCHRP 24-11 document provides a flow chart that allows the engineer to systematically conduct a series of iterations that result in an end product that is economical and safe.
Table 1. Typical inputs and outputs for design and analysis procedures.

<table>
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<tr>
<th>Performance Criteria/Indicators</th>
<th>Allowable total settlement</th>
<th>Allowable differential settlement</th>
<th>Factor of safety for slope stability</th>
<th>Factor of safety for overturning</th>
<th>Factor of safety for sliding</th>
<th>Factor of safety for bearing capacity</th>
<th>Factor of safety for seismic stability</th>
<th>Factor of safety against hydrostatic uplift</th>
<th>Factors of safety against pavement cracking and rutting</th>
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<tr>
<td>Subsurface Conditions</td>
<td>Site stratigraphy</td>
<td>Depth to groundwater table</td>
<td>Soil compressibility</td>
<td>Soil initial void ratio</td>
<td>Soil shear strength</td>
<td>Soil variability</td>
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<tr>
<td>Loading Conditions</td>
<td>Traffic surcharge</td>
<td>Fill/soil load</td>
<td>Structure load</td>
<td>Water pressures</td>
<td>Earthquake acceleration and duration</td>
<td>Wind load</td>
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<tr>
<td>Material Characteristics</td>
<td>Fill type</td>
<td>Fill density</td>
<td>Flammability</td>
<td>Fill water content</td>
<td>Fill creep</td>
<td>Fill susceptibility to petroleum products</td>
<td>Fill allowable load</td>
<td>Fill permeability</td>
<td>Freeze/thaw resistance</td>
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<td>Fill friction angle</td>
<td>Fill cohesion</td>
<td>Flexural strength</td>
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<td>Fill modulus/compressibility</td>
<td>Fill coefficient of lateral earth pressure</td>
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Table 1. Typical inputs and outputs for design and analysis procedures.

<table>
<thead>
<tr>
<th>Construction Techniques</th>
<th>Required compaction effort</th>
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<tbody>
<tr>
<td></td>
<td>Specialized fill placement</td>
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<tr>
<td>Geometry</td>
<td>Lift thickness</td>
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<td>Fill arrangement</td>
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<td>Side slope inclination</td>
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<td>Transition zone</td>
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References


