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ANALYSIS AND DESIGN OF EPS-GEOFOAM EMBANKMENTS FOR SEISMIC LOADING

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ABSTRACT: The use of block-molded expanded polystyrene (EPS-block) geofoam as a lightweight-fill material for highway embankments is a relatively mature geotechnology with more than 30 years history of successful application worldwide. Basic analysis and design procedures are now well established and documented, and current research and development efforts are focused on making incremental improvements. One such area of improvement relates to analysis and design for seismic loading. The recent construction of several EPS-geofoam highway embankments on the Central Artery/Tunnel (CA/T) Project in Boston, well known as the 'Big Dig', resulted in an opportunity to advance the state of practice for EPS-geofoam embankments subjected to seismic loading. In particular, a newly recognized behavioral mode referred to as *seismic rocking* was identified and found to govern the design of these fills for internal stability. This behavioral mode is described in this paper in the context of summarizing the current state of knowledge with respect to seismic analysis and design of EPS embankments.

INTRODUCTION

It has been more than 40 years since geofoams, which collectively are a type or family of cellular geosynthetics, were first used in engineered construction. During that time, expanded polystyrene (EPS) emerged as the clear geofoam material of choice for virtually all geofoam functions and applications identified to date, especially those dealing with transportation applications (Horvath 2004b). Comprehensive introductions to and summaries of the overall topic of geofoams can be found in several of references (Horvath 1995; PIARC 1997; Horvath 2001).

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One of the most common uses of EPS geofoam is in its block-molded form as lightweight fill for transportation-related earthworks. The first such application is believed to have been in 1972 for a road in Norway, and EPS blocks are now used routinely worldwide for highways, airfields and railways. In recent years, the U.S. Federal Highway Administration (FHWA) has recognized EPS-block geofoam lightweight fills as an important component of ground-improvement technology in its various educational programs for engineers in practice (USDOT 2004a, 2004b) as well as useful technology for *accelerated construction* (USDOT 2002).

Although the use of EPS-block geofoam as lightweight fill is now a relatively mature geotechnology, there are ongoing research and development efforts for the multiple purposes of documenting and standardizing the technology to facilitate its use by engineers in routine practice as well as incrementally improving the state of knowledge. An example of the former is U.S. National Cooperative Highway Research Program (NCHRP) Project No. 24-11. The final report (Stark et al. 2002) submitted for this project contained, among other things, design guidelines and material and construction standards created in a format that will hopefully form the basis for the first American Association of State Highway and Transportation Officials (AASHTO) documents covering all aspects of EPS-block geofoam fills for highway and road construction.

This paper is a contribution to incrementally improving the geotechnology of embankments constructed using EPS-block geofoam, specifically with regard to seismic analysis and design. This has been an area of increasing interest and importance worldwide ever since the use of EPS-block geofoam as a lightweight-fill material migrated in the mid-1980s from its early roots in Western Europe to geographic regions such as Japan and the U.S.A. where design for seismic loading is often necessary.

GENERIC EMBANKMENT CONFIGURATIONS

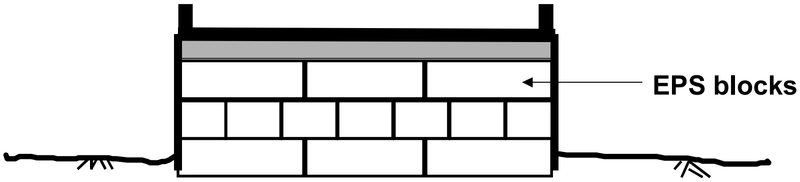
Embankments constructed using EPS-block geofoam as the principal material can be broadly divided into generic configuration categories using the following parameters:

- stand-alone versus side-hill geometry
- sloped- versus vertical-side(s).

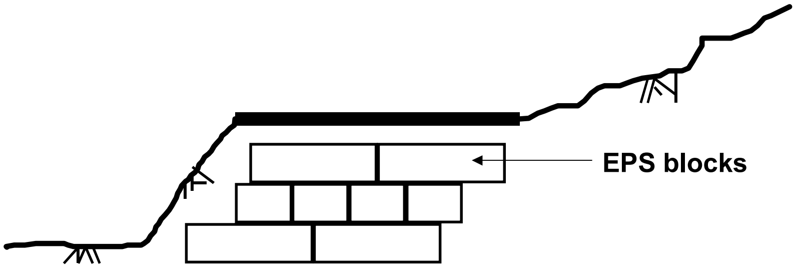
There are four possible combinations of these parameters. Figure 1 illustrates two and the remaining two can be easily visualized. It is of interest to note that in recent years the two combinations involving vertical-sided geometries have emerged as the ones of choice in most applications because of their overall efficient use of material and right-of-way.

CENTRAL ARTERY/TUNNEL PROJECT - CONTRACT C09C2

The Central Artery/Tunnel (CA/T) Project in Boston, Massachusetts, U.S.A., better known as the 'Big Dig', is a massive public-works undertaking in an unusually



(a)
stand-alone embankment with vertical sides



(b)
side-hill embankment with sloped side

FIG. 1. Examples of EPS-Block Geofoam Embankments

crowded urban area with relatively poor soil conditions and moderate seismic design requirements. One of the last segments of CA/T Project was Contract C09C2 titled "I-93/I-90 Interchange, Ramps and Surface Restoration at Albany Street" and referred to hereinafter as 9C2. This contract included the first permanent EPS-block geofoam lightweight fills on the CA/T Project.

The use of EPS-block geofoam for 9C2 was the key outcome of a cost-saving and schedule-reduction initiative undertaken in recognition of the accelerated-construction benefits of using EPS in an urban environment (Riad et al. 2003b). The overall redesign process for 9C2 considered a number of alternatives for lightweight-fill materials. On the basis of technical-and-cost assessments, EPS-block geofoam emerged as the primary choice for several road/bridge-approach embankments on this contract (Riad et al. 2004). Each of these embankments was of the stand-alone/vertical-side type shown in Figure 1(a).

Final design of these embankments included several technical innovations and advancements that were summarized by Riad et al. (2003a; reprinted in Horvath 2003). Two advancements related to seismic design are relevant to this paper and are discussed subsequently in some detail.

SEISMIC BEHAVIOR OF EPS-BLOCK GEOFOAM EMBANKMENTS

Overview

The seismic analysis or design of an embankment constructed using EPS-block geofoam is approached in the same basic, two-step procedure as would be used for any earthwork. The first step involves performing a basic, site-specific assessment to identify the ground motion to be used as the basis for the analysis or design. This first step will generally be the same regardless of the specific material(s) used to construct the earthwork. The second step involves considering the various seismic-response modes that are, to varying extents, unique to an EPS-block geofoam embankment.

Basic Analyses

The usual site-specific geologic and geotechnical-engineering investigations are conducted to define the relevant bedrock motion and subsurface stratigraphy overlying bedrock. If there is significant soil cover, the bedrock motion is 'brought up' through the soil column to the ground surface (which usually serves as the base of the earthwork) using either a site-specific computer analysis or amplification coefficients dictated by code. The details of this multi-step procedure are covered in detail in other publications. Kavazanjian et al. (1997) is one such references that is particularly relevant for transportation earthworks.

The specific seismic-design methodologies used in 9C2 were a combination of a consideration of the regional seismicity of the Boston area coupled with implementation of appropriate components of the 16th edition of the American Association of State Highway and Transportation Officials (AASHTO) "*Standard Specifications for Highway Bridges*" which was in effect at the time the 9C2 structures were designed. The horizontal component of bedrock acceleration was taken to be 0.17*g*. This had previously been established as the design criterion for the entire CA/T Project. As information, this reflects the current value of the theoretical bedrock motion with a 2% probability of exceedance in 50 years as published by the U.S. Geological Survey in 1996 (USGS 2004).

The soil stratigraphy overlying bedrock within the 9C2 contract area had a significant impact on design of the EPS-block geofoam embankments. On average, there was approximately 30 m (100 ft) total of pre-existing fill (much of the contract area had once been part of Boston Harbor), soft organic clay, and inorganic clay. Using the above-referenced AASHTO code as dictated by CA/T Project design criteria, this corresponded to AASHTO Type III conditions which, in turn, dictated a soil-column amplification coefficient of 1.5. The combined result was a design horizontal-acceleration magnitude of 0.255*g* at the existing ground surface which was also taken to be the bottom of the new embankments.

Modes of Seismic Behavior of an EPS-Block Geofoam Embankment

Overview

Regardless of how the design values of surface motion are obtained for a given site and project, the basic seismic response to the defined ground motion is fundamentally the same for each of the four configurations of EPS-block geofoam embankments noted previously. However, as discussed in the following sections it is now appreciated that there can be some important additional analysis and design considerations based on the specific nature and geometry of an embankment.

The seismic response of embankments constructed using EPS-block geofoam has been studied since the late 1980s using a combination of reduced- and full-scale shake-table testing, numerical analyses and observation of the behavior of actual structures. The vast majority of the published work on this subject has been performed in Japan. An assessment of the current state of knowledge (Nomaguchi 1996; Nishi et al. 1998; Hotta et al. 1998) indicates that the response of such embankments is complex. There are components of both flexible deformation and rigid-body displacement, both primarily in the horizontal direction. At the present time, routine practice is to decouple these different behavioral modes and analyze or design for each separately.

For each behavioral mode, only horizontal accelerations are typically considered. However, there is no reason why the vertical component of acceleration could not or should not be considered also as it does affect the effective weight of system components. There has been no known systematic study of the importance of vertical accelerations on the calculated behavior of EPS-block geofoam embankments.

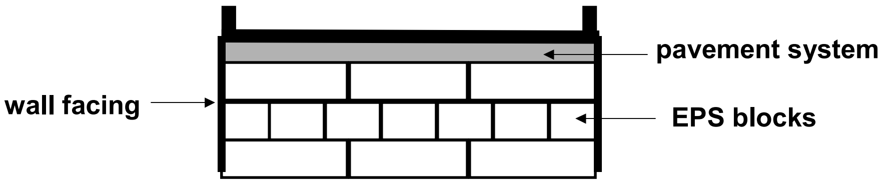
Horizontal Flexibility and Deformation (Lateral Sway)

In general, most structures of any type exhibit some flexibility and concomitant deformation in the horizontal direction when subjected to seismic shaking. This is referred to hereinafter as *lateral sway*. As a result of this flexibility, the horizontal motion that occurs at the base of a structure (typically the ground surface for analysis purposes) is almost always amplified by the structure. This is true for embankments in general (Kavazanjian et al. 1997) and those constructed of EPS-block geofoam in particular (Horvath 1995; Nomaguchi 1996). This horizontal amplification is important as the horizontal seismic-inertia forces acting on the embankment mass are linearly related to the amplified horizontal accelerations. Note that horizontal motion and amplification can occur in both the longitudinal and transverse directions of an EPS-block geofoam embankment although the latter is usually far more important in practice.

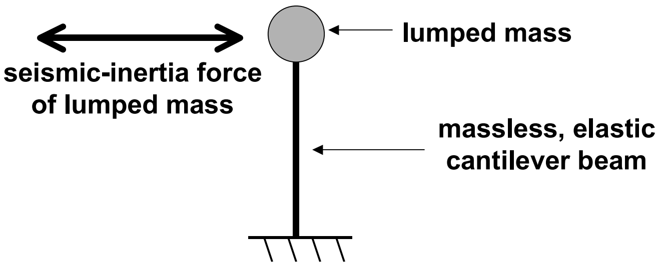
To analytically approximate this flexible behavior for EPS-block geofoam embankments, they have historically been modeled as a classical single-degree-of-freedom (SDOF) system as shown in Figure 2. Although the specific generic geometry of the 9C2 embankments is reflected in this figure (Figure 2(a)), the methodology described here is the same for the three other embankment geometries identified previously.

As shown in Figure 2(b), the SDOF system is visualized as a 'lollipop' consisting of a fixed-end, cantilevered Timoshenko beam (i.e. both flexural and shear components of bending are considered) composed of massless, elastic material and supporting a lumped mass at the top. The geometric (length, width) and elastic (Young's modulus, Poisson's ratio) properties of the beam are those of the assemblage of EPS blocks and the lumped mass is that of the material (pavement system primarily) overlying the assemblage of EPS blocks. These parameters are then used to calculate the fundamental period, T_o, of the system using a theory-based equation. A detailed discussion of this equation is presented in Horvath (1995) and Stark et al. (2002), with some updated comments in Horvath (2004a).

Once T_o has been determined, it can be used with the previously determined site-specific ground-surface acceleration and a site-appropriate response spectrum to determine the amplified horizontal acceleration of the lumped mass. System damping



(a)
actual embankment



(b)
traditional visualization of SDOF model

FIG. 2. Lateral-Sway Seismic-Analysis Model

for the response spectrum is assumed to come solely from energy losses within the assemblage of EPS blocks, both from internal material damping and inter-block sliding friction along joints (Horvath 1995; Stark et al. 2002). Calculation of the seismic-inertia force produced by the lumped mass (Figure 2(b)) is then straightforward. This force is used both directly (e.g. to check horizontal sliding of the pavement system on top of the EPS blocks) as well as indirectly (as part of analyzing additional behavioral modes as discussed subsequently) so is really a key element of the seismic analysis or design of an EPS-block geofoam embankment.

An alternative to using this theoretically rigorous approach involving a site-specific response spectrum would be to use some simplified methodology as is often presented in a design code. For example, the 16th edition of the AASHTO "*Standard Specifications for Highway Bridges*" that was used for 9C2 has an empirical formula for calculating the seismic-inertia force that is a function of T_o. It is worth noting that using a simplified approach such as this will generally result in conservative (i.e. overestimated in this case) magnitudes of the seismic-inertia force. This is because these empirical formulas are typically developed based on the relatively low percentage (1% to 2%) of critical damping that is associated with traditional bridge structures. Available information (Horvath 1995) indicates the damping that occurs within an assemblage of EPS blocks is always larger than this and thus would result in smaller seismic-inertia forces.

During the design-development phase of the 9C2 embankments, a critical review of the above-described analytical procedure for lateral sway raised the question of how the permanent covering on the sides of the embankments should be considered. Although an assemblage of EPS blocks with vertical sides as shown in Figure 1(a) and Figure 2(a) is inherently stable, it is necessary to cover the exterior vertical surfaces for durability and architectural considerations. The trend in U.S. practice in recent years has been toward using relatively massive precast reinforced or prestressed portland-cement-concrete panels. Consequently, such panels were considered during the initial design stages of the 9C2 embankments (they were not used in the final design for the reasons discussed in Riad et al. (2003a) and Horvath (2003)). Because such panels are usually connected to a reinforced-concrete load distribution slab placed above the assemblage of EPS blocks (such a slab is generally necessary whenever a vertical-side fill is used), it seemed reasonable that the mass of these panels should be considered in the seismic design.

An analysis was performed using a modification of the traditional model shown in Figure 2(b) to allow the mass of the side panels to be treated as a distributed mass along the entire length (height) of the cantilever beam. Space considerations preclude presenting details here but the result was that approximately 25% of the mass of the side panels was added to the lumped mass when calculating T_o.

Rigid-Body Translation

Many road embankments constructed using EPS-block geofoam serve as approach embankments to an elevated structure such as a bridge or viaduct. This is true of all the 9C2 embankments. Consequently, at one or both ends in the longitudinal direction of such an embankment the EPS blocks will be placed against a relatively rigid and non-yielding (non-displacing) abutment. Therefore, the lateral 'earth' pressure imposed on an abutment by the EPS blocks and overlying pavement system needs to be defined for both static and seismic load cases.

For all types of loading, the traditional assumption is that the material placed against the back of an abutment is sufficiently compressible so that the active earth-pressure-state will develop (Horvath 1995; Nomaguchi 1996). A detailed discussion of the resulting pressure diagram is presented in Horvath (1995) and Stark et al. (2002). It is worth noting that for the 9C2 embankments, a relatively thin (50 mm (2 in) thick) geocomposite drainage panel was placed in a vertical ('chimney') orientation between the back of each abutment and the EPS blocks. The specific drainage product used was one that has a relatively compressible core made of a geofoam material related to EPS. This was done so that that the panel would act as a *compressible inclusion* under seismic loading as well as provide positive drainage of any water that might enter the embankment from the surface.

Rigid-Body Rotation (Seismic Rocking)

During the design-development phase of the 9C2 embankments, the potential for a new mode of seismic behavior for EPS-block geofoam embankments in general was recognized and hypothesized by the first author. This mode is referred to hereinafter as *seismic rocking*. It is defined as rigid-body rotation of the entire embankment in a plane taken through its transverse direction due to the moment created by the relatively concentrated elevated mass of the pavement system. With reference to Figure 2, this rotation would occur in the plane of Figure 2(a) about an axis perpendicular to the figure and be caused by the seismic-inertia force shown in Figure 2(b).

While seismic rocking can, theoretically, occur with any EPS-block geofoam embankment, subsequent calculations indicated that it was critical for the 9C2 embankments because of their combination of a vertical-sided cross-section coupled with a relatively slender cross-sectional geometry (a height-to-width ratio of about one). This hypothesis and conclusion was confirmed by published literature (Nishi et al. 1998; Hotta et al. 1998) that was coincidentally obtained and reviewed by the second author at the time the 9C2 design-development work was beginning (early 2001). A careful reading of these references indicated that seismic rocking had apparently been observed for the slender EPS-block geofoam test embankments reported in those references but the mode itself was not recognized and identified as such.

The practical relevance and importance of seismic rocking is that the lowermost/outermost portions of an assemblage of EPS blocks can be subjected to relatively large vertical-normal-stress changes (both increases and decreases) due to the rocking motion. These stresses are due to what is referred to as the *M-c-on-I (Mc/I) effect*. The moment referred to in this case is that caused within the assemblage of EPS blocks by the seismic-inertia force shown in Figure 2(b). As noted previously, this moment acts within the plane shown in this figure about an axis perpendicular to this figure. This moment is obviously largest at the very bottom of the embankment. Note that these dynamic stresses must be added vectorially to the usual vertical-compressive stresses within an embankment due to gravity loads.

For the 9C2 embankments, it turned out that the largest vertical-compressive stresses for internal design (i.e. density selection) of the EPS blocks were at and near the very bottom of the embankment. This is exactly the opposite of what occurs within a typical EPS-block geofoam embankment based on consideration of gravity loads alone. This means that EPS blocks with appropriate material properties that can adequately accommodate these stresses must be placed in the lower portions of an EPS-block geofoam embankment as well as the upper portions as usually results from a design based on gravity-induced dead and live loads.

Strong support for these calculated results came from the aforementioned careful review of Nishi et al. (1998) and Hotta et al. (1998). When the EPS blocks were removed at the end of their tests, crushing of the EPS was found in exactly those areas where the stresses would be expected to be the largest in magnitude under seismic rocking. This crushing occurred because the EPS blocks at the bottom of these test embankments did not have the material properties necessary to accommodate the combined applied stresses from gravity loads and seismic rocking (in fairness to the researchers involved, they had not anticipated these combined stresses so had not designed for them explicitly).

CONCLUSIONS

Recent research and the experiences on Contract C09C2 of the Boston 'Big Dig' suggest the following for all EPS-block geofoam embankments constructed in geographical areas where seismic design is appropriate:

- The mode of seismic rocking should be considered for all embankment geometries. Experience to date indicates that this mode is likely to control design or be critical for vertical-sided embankments that are relatively slender in cross section. For structures that are already built that were not designed with consideration of seismic rocking, it may be desirable to analyze for this mode after the fact to see if preemptive retrofit is appropriate. This decision should be made on a case-by-case basis depending on the criticality of the structure.
- Considering the contribution of the mass of the exterior side covering of vertical-sided EPS-block geofoam embankments to the fundamental period, T_o, of the embankment in the lateral-sway analysis should also become a part of routine practice.

RECOMMENDATIONS

Seismic loading can play a significant role in the design of EPS-block geofoam embankments. Therefore, it would be useful contribution to the state of knowledge to pursue a program of research that involved explicit numerical modeling of the fully coupled seismic behavior of such embankments. This would allow an assessment of whether the current practice of performing a decoupled analysis for the flexible (lateral sway) and rigid (seismic rocking) components of seismic motion is reasonable and justified.

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