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Lateral Pressure Reduction on Earth-Retaining Structures Using Geofoams: Correcting Some Misunderstandings

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ABSTRACT: Block-molded expanded polystyrene and related geofoam materials can reduce lateral pressures acting on a wide variety of earth-retaining structures to almost zero under both gravity and seismic loading. There are two distinctly different functional ways to achieve this: lightweight fill and compressible inclusion. This paper updates the state of knowledge in this area with an emphasis on seismic buffers. This particular application, which makes use of the compressible-inclusion function, has seen increasing research interest in recent years. However there appear to be significant misunderstandings about material behavior that require clarification.

INTRODUCTION

Geofoam has been used as the generic term for a category of *cellular geosynthetics* since the early 1990s (Horvath 1995). As such, "geofoam" when used alone does not mean one specific material or product as many mistakenly believe but rather a wide spectrum of polymeric, vitreous, and cementitious materials and derivative products, each with a characteristic texture of small, closed, gas-filled cells so relatively numerous that the material has a lower density than normal earth materials.

Experience to date is that the common white polymeric foam called *expanded polystyrene* (EPS) is the geofoam material of choice for virtually all functional applications. Therefore this paper is limited to a consideration of EPS geofoam, specifically its generic block-molded form, and materials related to it.

SCOPE OF PAPER

A comprehensive documentation of the geosynthetic functions and applications for all geofoams was presented in Horvath (1995) with an updated bibliography in Horvath (2001). More recently, an assessment was made of the relative usage of the various geosynthetic functions and applications of EPS geofoam (Horvath 2005b). This indicated that the use of EPS geofoam to reduce lateral pressures on both new and existing earth-retaining structures (ERSs) has been significantly and surprisingly underutilized and under-researched to date even though such use dates back at least to the 1970s and experience indicates that it has the promise to revolutionize how ERSs are designed and constructed (Horvath 2004b). This underutilization is especially true for applications involving seismic loading so recent publications by the author (Horvath 2008a, 2008b) focused on this important application.

These publication efforts have had a positive outcome as recent years have seen a surge in research interest in using EPS geofoam with ERSs, especially as a *seismic buffer* (defined subsequently). Unfortunately, it appears from the published record that there may not be a clear understanding of relevant EPS material behavior. This complicates the interpretation and practical utility of published research outcomes. Consequently, after a brief overview of the mechanisms for achieving lateral pressure reduction on ERSs this paper focuses on seismic buffers with an intent to clarify the apparent misunderstandings for the benefit of future research into this topic.

EPS GEOFOAM AND EARTH-RETAINING STRUCTURES

A common term used in discussions related to ERSs is *yielding*. In this context "yielding" is synonymous with horizontal (lateral) displacement and can be applied to either the ERS itself or the ground adjacent to the ERS. With this in mind, ERSs are broadly divided into those that are:

- *non-yielding* which defines an ERS that is inherently incapable of and/or constrained against both rigid-body displacement and deformation in the horizontal direction under service loads. Common examples include basement walls of buildings, conventional bridge abutments, and otherwise free-standing rigid retaining walls that are either physically or geometrically restrained against displacement. The hallmark of non-yielding ERSs is that they are logically designed assuming the *at-rest* earth-pressure state within the retained soil; and

- *yielding* which defines an ERS that can either displace or deform or both in the horizontal direction under service loads. The hallmark of yielding ERSs is that they are assumed to be capable of developing the *active* earth-pressure state within the retained soil although they may or may not under service loads due to excess capacity ('safety') intentionally built into the overall system.

Not considered in this paper due to space limitations is a third type of ERS called *self-yielding*. These are rigid ERSs that displace horizontally on their own (usually as a result of thermal changes in their environment) as opposed to displacing (or not) as a reaction to applied earth loads as in the above-defined cases of non-yielding and yielding ERSs. Examples include *integral-abutment bridges* as well as various types of circular water- and wastewater-treatment tanks (Horvath 2000, 2004a, 2005a).

There are two distinctly different physical mechanisms by which EPS geofoam can be used to reduce lateral pressures on ERSs, with each mechanism utilizing a different geosynthetic function:

- The *lightweight-fill* function makes use of the fact that EPS has a density that is considerably less (as low as 1%) than that of soil; is inherently self-supporting even when EPS blocks are stacked vertically; and has a Poisson ratio that is very small. This is what is called a *small-strain function* of EPS geofoam.

- The *compressible-inclusion* function makes use of the fact that EPS can be manufactured and designed to be relatively compressible compared to the other materials with which it is in contact in order to intentionally induce horizontal displacements and concomitant shear-strength mobilization within the retained-soil mass (*controlled yielding*). This is a *large-strain function* of EPS-geofoam.

LIGHTWEIGHT-FILL FUNCTION

Fig. 1 shows a generic cross-section where blocks of EPS are used for this function. This function can be used effectively with both non-yielding and yielding ERSs. A detailed discussion of the current state of practice concerning the correct model for analyzing this functional application can be found in Horvath (2008a).

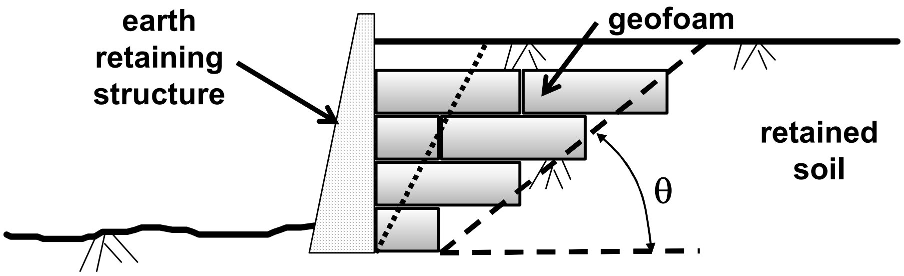

FIG. 1. Generic application of lightweight-fill function.

Of relevance to this paper is the common misconception that a classical active earth pressure wedge forms within the EPS blocks as indicated by the dotted line in Fig. 1. This simply does not occur. Rather, the EPS blocks act as an extension of the actual ERS so that the dashed line in Fig. 1 defined by the angle θ acts as a failure plane between the combined ERS + EPS mass and the retained soil, with the retained soil assumed to be in an active earth pressure state. The benefit of using EPS in this manner is due to the fact that a) the EPS blocks and overlying soil impart a relatively small lateral load on the ERS and b) the lateral earth pressure from the retained soil that is transmitted through the EPS blocks to the ERS under gravity and seismic conditions becomes zero if a sufficiently small value of θ as defined by Coulomb (for gravity loads) or Mononobe-Okabe (for seismic loads) theory is chosen.

COMPRESSIBLE-INCLUSION FUNCTION

The basic concept of a compressible inclusion is that a relatively low-stiffness geofoam material (EPS or related material) is intentionally placed between two stiffer materials (the ERS and adjacent ground). In such conditions the least-stiff material in the system (the EPS in this case) will compress much more readily than the others, resulting in load reduction through the classical soil mechanics mechanisms of shear-strength mobilization and arching within the adjacent ground (Handy 1985, Harrop-Williams 1989). These mechanisms were recognized and utilized at least as early as the early 20th century to reduce vertical loads on underground conduits (Spangler and Handy 1982). In these early conduit applications the compressible inclusion was some organic material such as bales of hay. The attraction of this concept is that it is very efficient and thus cost-effective material-wise as a relatively thin compressible inclusion, if properly designed, can result in significant load reductions on the ERS.

In its original and most basic form called the *Reduced Earth Pressure* (REP) concept (Fig. 2), a compressible inclusion is beneficial only for non-yielding ERSs as it is assumed the at-rest earth pressure state can be reduced only to the active earth pressure state through mobilization of the inherent shear strength of the retained soil.

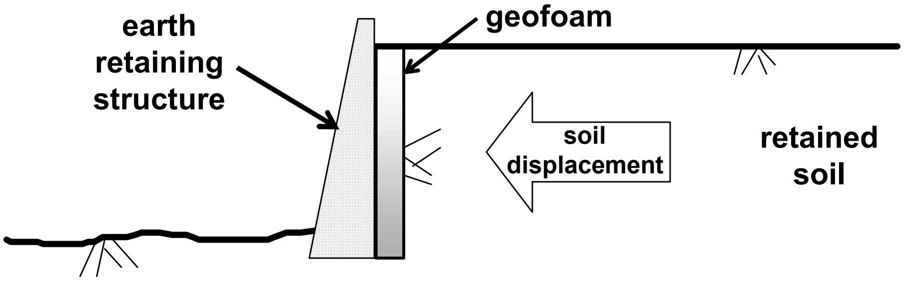

FIG. 2. Generic application of REP concept of compressible-inclusion function.

The original REP concept was subsequently extended by incorporating multiple horizontal layers of geosynthetic tensile reinforcement (geotextiles, geogrids, metallic strips or grids) within the retained soil and placed adjacent to the compressible inclusion in the classical arrangement of *mechanically stabilized earth* (MSE). This is called the *Zero Earth Pressure* (ZEP) concept because the system can be designed to allow the reinforcement to strain and behave in a classical *mechanically stabilized earth wall* (MSEW) mechanism. Thus the ZEP concept can produce benefits for both non-yielding and yielding ERSs as it is possible to reduce lateral pressures to less than the active state and approaching zero (hence the name used for this concept).

Space limitations preclude a detailed discussion of the current state of practice concerning models for analyzing the REP and ZEP concepts. Only an overview is presented here. Details concerning analytical models used to date can be found in Horvath (1996, 1997, 1998a, 1998b, 2008a).

The basic physical model used for analyzing both REP and ZEP applications is that of a mechanical system consisting of two axial springs aligned horizontally and placed in series. Each spring, which may be linear or non-linear as desired, represents the horizontal force-displacement behavior of a system component as follows:

- The retained soil, unreinforced or reinforced as appropriate, has an initial compressive force (typically assumed to be the at-rest state) that reduces with increasing horizontal displacement ('spring' extension) to either the active state (REP concept) or zero (ZEP concept). The magnitude of displacement required to reach these minima is problem-specific.

- The geofoam compressible inclusion has zero initial force that increases with increasing horizontal displacement ('spring' compression). Note this implies that the compressive stiffness normal to the primary direction of soil displacement (horizontal in this case) is the relevant physical property of the compressible inclusion. For the purpose of quantifying this stiffness it was found useful to define a new dimensionless parameter, λ, called the *normalized compressible inclusion stiffness* (Horvath 2000):

$$\lambda = \frac{E_{ci} \cdot H}{t_{ci} \cdot p_{atm}} \qquad \textbf{(1)}$$

where E_{ci} is the Young's modulus of the compressible-inclusion material; H is the 'geotechnical' height of the ERS (i.e. height of the retained soil against the back of the ERS); t_{ci} is the thickness of the compressible inclusion; and p_{atm} is atmospheric pressure (used solely to non-dimensionalize λ). The limiting values of λ are zero for the 'perfectly compressible' case of unrestricted displacement and infinity for the 'perfectly rigid' case of no displacement.

SEISMIC BUFFERS

In recent years the predominant area of research into the use of EPS geofoam to reduce lateral pressures on ERSs has been the REP concept (Fig. 2) under seismic loading. During this time the term *seismic buffer* has been coined by others and is now widely used for this specific application of the REP concept. Zarnani and Bathurst (2009) provide an overview and summary of recent research into seismic buffers that is current as of the time this paper was written (early 2010).

The most significant outcome of recent research is that the effectiveness of seismic buffers in terms of relative reduction of seismic forces compared to a baseline of no compressible inclusion depends on the natural frequency of the ERS-inclusion-retained soil system compared to the frequency of the applied cyclic load. Earlier work (Horvath 1997, 1998b) assumed load reduction was frequency-independent.

However, this recent research appears to unilaterally suffer from potentially significant flaws due to apparent fundamental misunderstandings of the mechanical (stress-strain-time-temperature) properties of the geofoam materials and products that were used in those studies as the compressible inclusions. To what extent these flaws impact the conclusions of this published work is unknown at this time and beyond the scope of this paper. The intent of this paper is to explain what these flaws are and what the correct interpretation should be. It is then left to others to revisit, revise, correct, and re-publish, as necessary, past research. Future research will hopefully be planned, executed, and interpreted correctly from the start.

The basic flaw in previous research involves proper understanding and assessment of the stiffness of the geofoam compressible inclusion. Compressive stiffness is the single most important behavioral characteristic of any compressible inclusion and as indicated in Eq. 1 Young's modulus is the material stiffness parameter of primary interest. However, most research to date (e.g. Bathurst et al. 2007) has placed undue focus and importance on the density of the EPS based on the assumption that EPS stiffness is proportional to its density. This is both misleading and simply incorrect as a general rule (Horvath 2009).

In general, the density of EPS in and of itself means absolutely nothing with regard to its stiffness. It is believed the common misconception that there is a relationship between EPS density and stiffness (in the form of Young's modulus) derives from the fact that in a very limited context involving relatively small compressive strains (less than 1%) and assuming certain important quality-assurance measures have been met then correlations (typically linear) between EPS density and Young's modulus have been observed by many researchers worldwide (Horvath 1995). However, as noted previously compressible-inclusion applications in general and seismic buffers in particular are inherently large-strain in nature. Therefore, any small-strain correlations between EPS density and modulus are simply irrelevant.

It appears that in more-recent publications (e.g. Zarnani and Bathurst 2009) researchers have begun to get away from using EPS density as a measure of its stiffness and are using Young's modulus directly as the primary correlation variable with material behavior in seismic-buffer applications. While this is certainly a step in the right direction it does not appear that the proper moduli have been used in analyses.

To begin with, there are two distinctly different EPS-based geofoam materials that have been studied by researchers and used in practice for compressible inclusions. The mechanical behavior of each material is markedly different even though the materials look identical and may even have identical densities. One material is 'normal' block-molded EPS that has the uniaxial unconfined compressive behavior depicted qualitatively by Curve 1 in Fig. 3. Upon initial loading, normal EPS has a very limited nominally linear-elastic range up to a compressive strain of approximately 1%. This is followed by a transition zone of significant yielding that is the result of physical distortion of the originally-spherical cells that comprise the EPS so that the cells become permanently ellipsoidal in shape. There is then an extended zone of slight work-hardening and finally a zone of significant work-hardening as the EPS is literally crushed back to solid polystyrene. Note that once the zone of yielding is passed even one time there is significant and permanent non-recoverable ('plastic') strain upon unloading as shown by a typical post-yield unload-reload portion of Curve 1. Note also that the scale of the stress axis in Fig. 3 is intentionally unlabeled as it is dependent on not only the EPS density but also strain-rate and temperature.

The most important point made here is that the Young's modulus of EPS, which is the slope of any point on Curve 1, is constantly varying once the initial nominal linear-elastic zone is passed. So the Young's modulus of normal EPS is dependent not only on the initial material density but also stress level, stress history, strain-rate, and temperature as well. All of these factors are significant for seismic-buffer applications where cyclic compressive strains well into double-digits and certainly well beyond the linear-elastic limit of approximately 1% strain are the rule.

Unfortunately, it appears that researchers to date have not appreciated the complex factors affecting the Young's modulus of EPS as they affect seismic-buffer applications, especially given the large strains and cyclic loading involved, as correlations for Young's moduli applicable for small-strain (i.e. < 1%) applications have been used in research to date (e.g. Zarnani and Bathurst 2009).

The other material used for compressible inclusions is what is called *resilient* or *elasticized* EPS. This is normal block-molded EPS that has been subjected to an

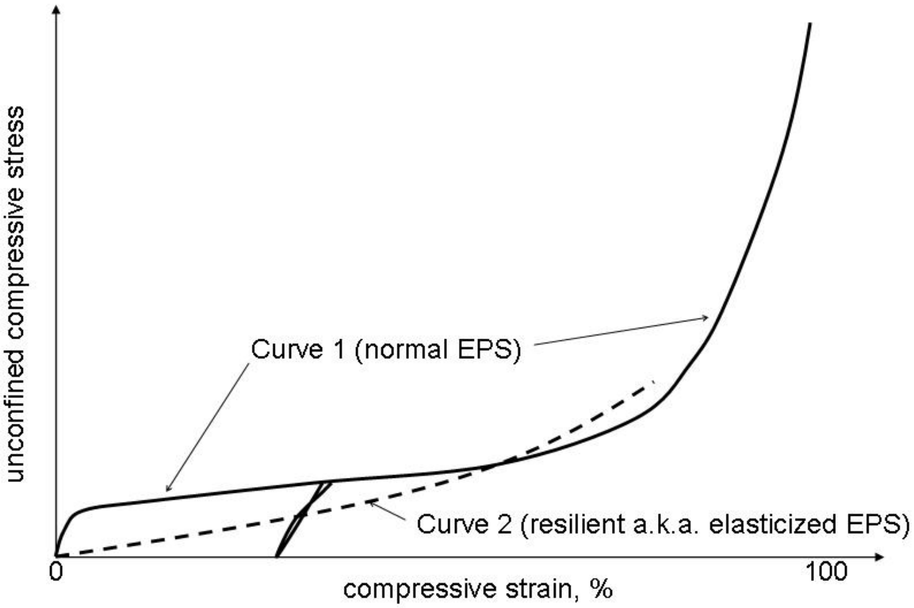

FIG. 3. Generic stress-strain behaviors of block-molded EPS and related materials

additional manufacturing step to permanently distort the cell shapes before the material is loaded in service for the first time. The benefit of doing this is that the stress-strain behavior of the material is permanently and markedly different compared to normal EPS. The behavior of resilient EPS is shown as Curve 2 in Fig. 3. Note that this comparison is for resilient EPS that originally had the same density as the normal EPS (Curve 1) depicted in the same figure. This emphasizes the point made previously that EPS that has the same density may have very different stiffness properties both qualitatively and quantitatively.

CONCLUSIONS

The efficacy of using block-molded EPS geofoam and related materials such as resilient EPS to reduce lateral pressures acting on ERSs is well established. However, research is still needed in many areas for both the lightweight-fill and compressible-inclusion functional applications to both better understand the behavior of the ERS-geofoam-retained soil systems as well as to both verify and improve, as necessary, current analysis and design methodologies. The key element in this overall process is that the very complex material behavior of EPS as it is relevant to a particular functional application must be clearly understood if research is to be properly formulated, executed, interpreted, and presented in publications.

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