

Seismic Lateral Earth Pressure Reduction on Earth-Retaining Structures Using Geofoms

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ABSTRACT: *Geofoam* is a type of *cellular geosynthetic* that can be used to reduce lateral earth pressures acting on a wide range of earth-retaining structures (ERSs). There are two distinct geosynthetic-functional ways in which geofoms can provide this benefit: as *lightweight fill* and as a *compressible inclusion*. These functions can be implemented either in new construction or retroactively with existing ERSs. Depending on the specific design details chosen, it is possible to reduce lateral earth pressures acting on an ERS to almost zero under both gravity and seismic loading. Unfortunately, the existence and capabilities of this geotechnology, which has the potential to revolutionize the way ERSs are designed, are still not widely known and thus have been significantly underutilized to date. This paper summarizes the state of knowledge concerning the use of geofoms to reduce lateral earth pressures on ERSs and addresses both analytical methods (with an emphasis on seismic loading) as well as geofom materials and products. It is hoped that this will encourage both usage and research of this intriguing geotechnology.

INTRODUCTION

One of the important advances in geosynthetic geotechnology in the final years of the 20th century was the recognition that there are categories of geosynthetic beyond the traditional two-dimensional/planar types such as geotextiles, geomembranes, and geogrids. In particular, a type of geosynthetic called geofom was defined that encompasses a wide spectrum of materials, each with a characteristic texture of small, closed, gas-filled cells so relatively numerous that the resulting material has a porosity that is typically greater than 90% (i.e. a void ratio in excess of 1000%) with a concomitant very low density compared to normal earth materials (Horvath 1991; 1992a,b,c; 1995). It is important to note that geofom is the generic term for all closed-cell synthetic materials used in geotechnical applications and is not limited to one material or product. Geofoms, along with *geocombs* and *geocells*, are now recognized collectively as cellular geosynthetic where product geometry and performance are distinctly three-dimensional in nature.

Some of the geotechnically significant general attributes of geofoms are that they:

- offer geosynthetic functions that, with few exceptions, are not provided by any other type of geosynthetic. Thus geofoams provide the design professional with design alternatives that would otherwise not be available;
- are inherently *multifunctional* which means that one geosynthetic product consisting of or incorporating geofoam can provide two or more distinct geosynthetic functions. This increases the cost effectiveness of using geofoam-based products because more than one technical benefit can be attributed to a single product; and
- synergistically complement traditional planar geosynthetics, especially those that provide tensile reinforcement (geogrids, geotextiles, metallic elements), to provide design professionals with innovative design alternatives that no one geosynthetic alone can provide.

BACKGROUND

Introduction

A comprehensive overview of geosynthetic functions and applications for geofoams was presented in Horvath (1995) with an updated bibliography in Horvath (2001). More recently, a survey was made of the relative state of usage of the various geosynthetic functions of geofoams (Horvath 2005b).

Prominent in these publications was information concerning the use of geofoams to reduce lateral earth pressures as this particular application has the promise to revolutionize how ERSs are designed and constructed (Horvath 2004c). Although this particular geofoam application dates back to at least the 1970s experience indicates that it has been significantly under-researched and underutilized to date. Furthermore, what research and practical application have occurred to date have largely focused on gravity loads. Consequently, the purpose of this paper is to focus on analytical methods used for seismic loads. Both what is already known as well as where improvements in the state of knowledge are needed are identified and discussed. Thus it is hoped that both practitioners and researchers will find this paper of use, and that it will both inform and inspire so that there is both greater utilization of as well as increased research into the use of geofoams with ERSs.

Terminology

A common term used in discussions related to lateral earth pressures and ERSs is *yielding*. In this context, yielding is synonymous with horizontal (lateral) displacement and is used solely in this context throughout this paper.

Types of Earth-Retaining Structures

ERSs are broadly divided into those that are:

- *non-yielding* which defines an ERS that is inherently incapable of and/or constrained against both deformation and displacement in the horizontal direction under design loads. Common examples include below-grade (e.g. basement) walls of buildings, bridge abutments, and free-standing retaining walls that are restrained against horizontal displacement due to physical restraint or structure geometry. 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 design 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.

Not considered in this paper, although noted here for the sake of completeness, 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 surrounding environment) as opposed to displacing (or not) as a reaction from earth loads as in the classic cases of yielding and non-yielding ERSs. Examples include *integral-abutment bridges* as well as various types of circular water- and wastewater-treatment tanks (Horvath 2000, 2004b, 2005a).

Relevant Geofam Functions

There are two primary mechanisms by which geofams can be used to reduce the lateral pressures on ERSs, with each utilizing a different geosynthetic function:

- The lightweight-fill function makes use of the fact that geofams have a density that is considerably less (as low as 1%) than that of soil; are inherently self-supporting even on a vertical slope; and can have a Poisson's ratio that approaches zero. This is a *small-strain function* of geofams.
- The compressible-inclusion function makes use of the fact that geofam materials can be designed to be relatively compressible to intentionally induce horizontal displacements and concomitant shear-strength mobilization within the retained-soil mass (called *controlled yielding*). This is a *large-strain function* of geofams.

It is relevant to note that regardless of the specific type of ERS or geofam functional application utilized there is practical applicability not only for new construction but with existing structures. The latter is useful in practice as it is often a better design alternative to reduce the loads on an existing ERS as a way of upgrading its current and/or future performance as opposed to modifying or replacing the ERS to accept greater loads. Relevant to the theme of this conference is that this design strategy of load-reduction can be a cost-effective way to seismically upgrade an existing ERS that was not designed originally with a consideration of seismic loads or was designed for seismic loads of smaller magnitude than those required by current design codes or good practice.

LIGHTWEIGHT-FILL FUNCTION

Application Concept

Figure 1 shows a generic cross-section where geofoam is used for its lightweight-fill function. The details of the ERS are irrelevant for the present discussion as this function can be used effectively with both non-yielding and yielding ERSs. Note that nowadays the geofoam would be configured as shown in this figure with a stair-stepped interface between geofoam and retained soil when viewed in cross-section. The importance of this stepped geometry was not always recognized in the past.

Analytical Model

The current state of knowledge indicates that the behavior of the geofoam mass as shown in Figure 1 is much more complex than usually thought. A common perception is that a classical active-earth-pressure 'wedge' forms within the geofoam mass as shown qualitatively by the dotted line in Figure 1. The presumed benefit of the geofoam is that its unit weight is substantially less than that of soil and thus the active earth force that this hypothetical wedge imparts on the back of the ERS is proportionately reduced compared to soil using a classical equivalent-fluid-pressure distribution along the back of the ERS.

However research to date indicates that this behavioral mechanism, although intuitive, is completely incorrect as it is based on a simplistic extrapolation of what occurs with a soil mass of essentially unlimited lateral extent behind an ERS. In reality, as shown in Figure 1 two very different materials (geofoam and soil) are in close proximity behind an ERS and the interaction of these materials must be taken into account to develop the net result on the back of the ERS.

The current state of practice assumes that the geofoam mass acts as a pseudo-ERS independent of, but interacting with, the actual ERS (note that a geofoam mass can be designed to be entirely self-supporting without an ERS in which case it is called a *geofoam wall*). The retained soil is assumed to act on the geofoam mass along an imaginary plane defined by the angle θ and dashed line in Figure 1. Furthermore, it is assumed that the active-earth-pressure state always develops within the retained soil adjacent to the geofoam mass whether the actual ERS is non-yielding or yielding. This is because it is assumed there is always sufficient lateral compression within the geofoam mass to allow the retained soil to displace sufficiently to mobilize the active state. Thus the earth forces applied to the geofoam mass by the retained soil under

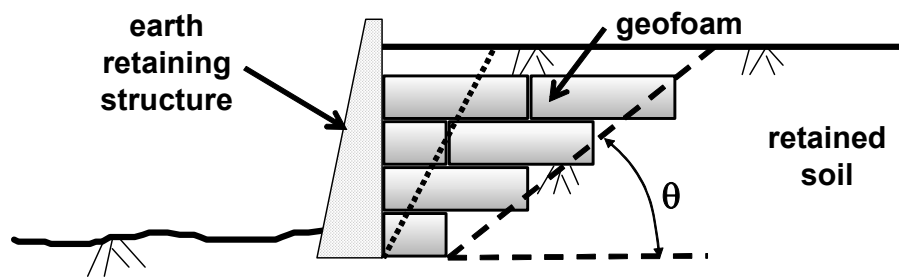


FIG. 1. Generic application of lightweight-fill function.

seismic loads can be estimated in the usual way using, for example, the classical Coulomb and Mononobe-Okabe theories. These earth forces are assumed to be transmitted through the geofoam mass to the back of the ERS.

The magnitude of forces from both the Coulomb and Mononobe-Okabe theories are dependent on the angle θ which is dictated by the geofoam geometry chosen. Thus it is through appropriate selection of the angle θ that geofoams achieve both gravity- and seismic-load reduction using the lightweight-fill function. Note that there is always a magnitude of θ for which both the gravity and seismic earth loads applied to the geofoam mass will be zero, although the θ -values are different. Of course in any project-specific application it is not necessary to reduce these forces to zero but this does indicate the significant reduction in earth forces that can be achieved in concept when using the lightweight-fill function of geofoam, albeit requiring use of a relatively large volume of geofoam to achieve this. Thus in any project-specific application the actual value of θ used needs to be optimized to where the combined costs of the ERS and geofoam material are minimized.

Additional forces are assumed to act on the back of the ERS as a result of the mass of material (soil, pavement, etc.) lying above the geofoam (the mass of the geofoam itself is negligible under both gravity and seismic loading):

- A static component exists under both gravity and seismic loading. It consists of a classical equivalent-fluid-pressure distribution within the thickness of material overlying the geofoam mass (at-rest or active conditions are assumed depending on whether the ERS is non-yielding or yielding respectively) plus a uniform-pressure distribution within the full thickness of the geofoam mass equal to one-tenth of the vertical stress acting on the top of the geofoam mass.
- A dynamic component exists under seismic loading only. It is based on the assumption that the geofoam mass and any overlying material act together as a flexible system modeled as a classical single-degree-of-freedom system where the geofoam acts as the spring and dashpot/damper components and the overlying material represents the lumped mass. Guidelines for numerically evaluating the various model parameters can be found in Horvath (1995, 2004a) and Stark et al. (2004a). For yielding ERSs only this component of load is reduced by a horizontal shear force that is assumed to develop along the horizontal portions of the stepped interface between the geofoam and underlying ground. This shear force is calculated using the vertical stress applied to the top of the geofoam and the friction angle between the geofoam material and underlying ground.

Suggestions for Future Improvements

The above-described analytical model and its various assumptions are the collective result of relatively limited research and observation of actual ERSs, much of which was not well documented in published literature (Horvath 1995). In particular, the assumptions concerning load components attributable to seismic loading, i.e. the uncoupled analysis of forces acting on the ERS from the retained soil versus those from the geofoam with overlying material, are considered particularly tentative at this

time even though they have been in use since the 1990s. Therefore it is suggested that the entire analytical model and concomitant assumptions used to perform an analysis of geofoam used for its lightweight-fill function to reduce lateral earth pressures be critically studied and reviewed using the entire gamut of modern numerical and physical testing.

COMPRESSIBLE-INCLUSION FUNCTION

Application Concept

Overview

Experience indicates that the geosynthetic function of compressible inclusion is not intuitive to many design professionals (Horvath 2005b), even though it utilizes the fundamental soil-mechanics principle of arching (Handy 1985, Harrop-Williams 1989) that was recognized and utilized in the early 20th century, if not before that, to reduce vertical loads on underground conduits (Spangler and Handy 1982; Horvath 1995, 1996, 1998a, 2004c). This coupled with the fact that geofoams are identified so closely and, in many cases, exclusively with the lightweight-fill function has led to an overall lack of knowledge and use of this geofoam functional application to date.

In its most basic form, utilizing a geofoam compressible inclusion produces a benefit only for non-yielding ERSs. However this concept can be extended by incorporating geosynthetic tensile reinforcement within the retained-soil mass. In this latter configuration there are benefits for both non-yielding and yielding ERSs.

The basic concept of a compressible inclusion is that a relatively low-stiffness material is intentionally placed between two stiffer materials. In such conditions the least-stiff material in the system will compress much more easily than the other materials, resulting in load reduction through some soil-mechanics mechanism such as, but not limited to, arching (different mechanisms occur with expansive soil for example). The attraction of this concept is that it is very efficient material-wise as a relatively thin compressible inclusion can result in significant load reductions.

It is of relevance to note that the compressible-inclusion function of geofoams is a *large-strain* geofoam application, i.e. one where relatively large compressive strains of the geofoam product are intended under design loads. This contrasts to the lightweight-fill function such as shown in Figure 1 which is a *small-strain* geofoam application where compressive strains under design loads must be kept relatively small in magnitude for the design life of the structure.

Reduced-Earth-Pressure (REP) Wall Concept

The original, basic concept for using a geofoam compressible inclusion to reduce lateral earth pressures on an ERS is illustrated generically in Figure 2. Again, the ERS details are irrelevant although it is worth noting that this application is used only with non-yielding ERSs. Essentially, the function of the compressible inclusion in this application is to allow a mass of retained soil to displace laterally and mobilize its inherent shear strength even if the ERS does not displace or deform, essentially

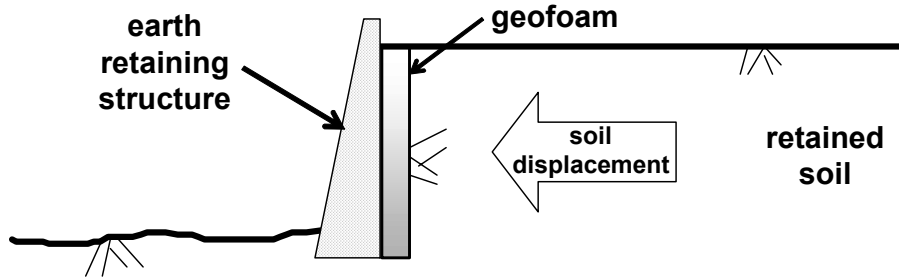


FIG. 2. Generic application of REP concept of compressible-inclusion function.

transforming a non-yielding ERS into a yielding ERS in the process. Because lateral earth pressures reduce in magnitude from the at-rest to active state as the retained soil displaces this is referred to as the *Reduced-Earth-Pressure* (REP) concept.

Zero-Earth-Pressure (ZEP) Wall Concept

The original REP concept was extended circa the 1980s as shown in Figure 3 by incorporating multiple layers of geosynthetic tensile reinforcement (geotextiles, geogrids, metallic elements) within the retained soil in the classical arrangement of *mechanically stabilized earth* (MSE). In this application, compression of the geofabric and resulting horizontal displacement of the reinforced soil mass allows the reinforcement to strain and develop tensile forces even in situations where little or no displacement or deformation of an ERS would not allow this to develop, thus rendering the reinforcement of little or no value. Because the lateral earth pressures in this case can reduce in magnitude from the at-rest state to effectively zero as the retained soil expands horizontally and the tensile reinforcement strains this application is referred to as the *Zero-Earth-Pressure* (ZEP) concept.

Analytical Models

The basic physical model used to date for both REP and ZEP applications is that of a system consisting of two springs in series. Each spring, which may be linear or non-linear as desired, represents the horizontal force-displacement behavior of a system component. Referring to figures 2 and 3:

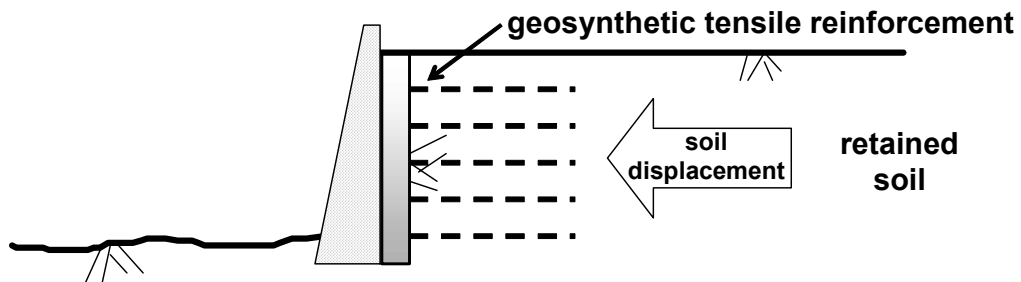


FIG. 3. Generic application of ZEP concept of compressible-inclusion function.

- The unreinforced (REP concept) or reinforced (ZEP concept) mass of retained soil is a spring with an initial horizontal compressive force (typically assumed to be that of the at-rest earth pressure state) that reduces with increasing horizontal displacement to either the active state (REP concept) or zero (ZEP concept).
- The geofoam compressible inclusion is a spring with zero initial force that develops a horizontal compressive force with increasing horizontal displacement.

The solution is found by matching forces and displacements in the springs. The resulting force is that assumed to be acting on the ERS.

The most complex aspect of this model is properly quantifying the force-displacement behavior of the retained soil (Horvath 2000). In the case of the REP concept, the minimum horizontal force assumed to develop corresponds to the active earth pressure state and can be estimated using the classical Coulomb and Mononobe-Okabe theories for gravity and seismic loads. The Veletsos and Younan (1994) solution for a yielding ERS under seismic loading has been extended for use with the REP concept to provide an alternative solution (Horvath 1997, 1998b, 2005b, 2008).

Efforts to date relative to the ZEP concept have been much more limited and have considered gravity loads only (Horvath 2000). A key problem is that MSE design is typically failure-, not displacement-, based so quantifying the force-displacement behavior of a MSE mass is difficult. One item under current consideration is to see if an elasticity-based solution such as that developed by Harrison and Gerrard (1972) might provide useful insight. In any event, one characteristic of the ZEP concept is that the minimum horizontal force assumed to develop within the reinforced soil mass always becomes zero at some finite displacement.

Suggestions for Future Improvements

The analytical models for the compressible-inclusion function of geofoam for use with lateral-earth-pressure reduction are relatively much less researched and developed than those for the lightweight-fill function, especially for the ZEP concept. Therefore as a group they should be considered a work-in-progress and in need of future research to either validate them or develop other models.

GEOFOAM MATERIAL SELECTION

Despite the relatively recent recognition of closed-cell foams as geosynthetics and the use of the term geofoam to identify them generically as a group, such materials have actually been in commercial use since at least the 1950s and used in geotechnical applications since at least the early 1960s. Consequently, geofoams have a longer history of use than most other geosynthetics and there is extensive practical experience concerning both the in-ground performance and relative economics of various closed-cell foams as geofoam geosynthetic. A comprehensive discussion of geofoam materials can be found in Horvath (1995).

This collective experience indicates that the geofoam material of choice worldwide for most functional applications is *expanded polystyrene* (EPS). This is the familiar

white polymeric (plastic) foam commonly known for its various consumer applications for beverage cups and cushion packaging. For geofoam applications it is typically used in the form of prismatic blocks or panels created in a process called *block molding*.

Consistent with the dominance of block-molded EPS as the overall geofoam material of choice is that it is the material of choice when using the lightweight-fill function for lateral-earth-pressure reduction as shown in Figure 1. Detailed guidance on how to rationally design for this application can be found in Stark et al. (2004a). It is important to note that EPS used for this application is a generic, commodity material that is typically bid on a price-competitive basis in practice. Experience has clearly demonstrated the need for, and rigorous enforcement of, detailed project-specific specifications based on appropriate standards such as contained in Stark et al. (2004b) or ASTM (2004, 2005) as the basis for helping ensure delivery of technically acceptable material for a project. This includes the need for independent manufacturing quality assurance (MQA) of all EPS blocks delivered for a project.

While block-molded EPS geofoam has been used for compressible-inclusion applications experience indicates that it is far more efficient and cost-effective to use a more-compressible material. Both *resilient (elasticized) EPS* and *porous-polystyrene block* have been used successfully for this application. These materials are discussed in detail in Horvath (1995). When sold alone or in combination as panel-shaped products for the geofoam market these are both proprietary in nature.

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