

**EXPANDING THE USE OF
EXPANDED POLYSTYRENE (EPS) GEOFOAM IN PRACTICE**

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ABSTRACT: Most geotechnical and structural engineers are now aware of the well established and proven use of expanded polystyrene (EPS) geofoam as a lightweight fill material. However much less well known and utilized to date in practice are the many other functional applications of EPS geofoam, most of which cannot be provided by any other geosynthetic product. Therefore greater use of these unique functions would provide both design professionals and end users with design alternatives and problem solutions that are simply not available with any other type of geosynthetic.

Of all the underutilized functional applications of EPS geofoam, perhaps the most significant in terms of its potential for widespread use and concomitant practical impact on constructed facilities is the function of compressible inclusion. This paper provides a brief overview of all the geosynthetic functions that can be provided by EPS geofoam and derivative products, and then focuses on the use of the compressible inclusion function.

1.0 INTRODUCTION

1.1 Background

The overall use of cellular geosynthetics (geofoams and geocombs) has increased dramatically worldwide in recent years (Horvath 2004b), with most of this growth centered around various geofoam products made from block- or shape-molded expanded polystyrene (EPS), derivative materials such as resilient (elasticized) EPS, and related materials such as glued polystyrene porous block. This is because EPS (this acronym is used hereinafter in this paper in a broad context to refer to not only basic EPS but derivative and related materials as well) has proven to be the material of choice for a combination of technical and economic reasons in the vast majority of situations where a cellular geosynthetic can be used.

This overall growth in cellular geosynthetics geotechnology in general and EPS geofoam in particular has been a classic example of the application of what the author defined in 2001 as the "trilogy-of-technology" concept. This is a group of three complementary, synergistic, never ending actions that are necessary to develop, maintain, and grow any technology. This trilogy consists of:

- technology advancement through research and development,
- technology transfer (T²) through education of users of a technology, and

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- technology documentation through the development of relevant quality control (QC) and quality assurance (QA) standards for materials, products and construction activities to allow a technology to be used with confidence.

The trilogy-of-technology concept can be likened to or visualized as being a three-legged stool. Should any leg be significantly shorter than the others or even missing completely then the stool is inherently unstable. Stability requires that each leg of the stool be both present and of essentially equal length. So too must equal attention be given to all three of the above aspects of a technology if that technology is to flourish and grow.

In the case of cellular geosynthetics in general and EPS geofoam in particular, the recent rapid growth after decades of only very modest advancement has been the result of proactive, aggressive initiatives made simultaneously in several areas that fit within this overall trilogy-of-technology framework:

- greater awareness of the basic technology by both design professionals (civil engineers and architects) and end users (builders and contractors) as a result of numerous publications, presentations, Internet websites, and other T² initiatives as typified by this seminar;
- increasing explicit acknowledgement and support by government agencies such as the U.S. Federal Highway Administration (FHWA) and Transportation Research Board (TRB). This recognition is multi-faceted and is both for the direct technical benefits of the technology (as typified by the FHWA's promotion of EPS geofoam as lightweight fill in road construction through their "*Get in, get out, and stay out with EPS geofoam*" theme (see www.fhwa.dot.gov/rnt4u/ti/eps.htm)) as well as for the indirect and less obvious financial and social/political/public-relations/environmental benefits of accelerated construction (see www.fhwa.dot.gov/rnt4u/ti/accel_const.htm). These efforts by the FHWA complement the recent publication of landmark research and design documents (which included long needed guideline standards and specifications) for the use of EPS geofoam as lightweight fill that was funded through the U.S. National Cooperative Highway Research Program (NCHRP) and administered by the TRB (Stark et al. 2004a, 2004b);
- the development of new materials and products;
- the development of new functional applications for existing materials and products; and
- ongoing expansion of the knowledge base (e.g. improved understanding of material behavior, improved and additional analytical methods, improved and new design details) for well established, mature functional applications such as EPS lightweight fill for road construction (Riad et al. 2003a, 2003b, 2004; Horvath 2004a; Riad and Horvath 2004; Riad 2005).

As but one example of the last item, a companion paper to this seminar (Riad 2005) focuses on several recent, significant technical advances in the use of EPS geofoam as lightweight fill in road construction, a well known and widely used application that has been used successfully worldwide since at least 1972. The fact that there can be multiple technological advances, and several first-of-their-kind significant ones at that, on just one project alone (the world famous

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Boston 'Big Dig') clearly indicates that there are benefits to continued research and development initiatives even for well known, commodity applications such as this.

1.2 Purpose and Scope of Paper

Technology development as defined by the trilogy-of-technology concept is a never ending cycle. Experience indicates that there is no technology, no matter how mature in its development and use, that cannot benefit from at least periodic reassessment in light of current technological developments, market demands and market economics. As a result, to support and sustain a technology there must be an ongoing effort to identify and prioritize areas needing attention.

Toward this end, the overall theme of this paper and its accompanying presentation at this seminar is to explore future trends in the use of EPS-geofoam products beyond the traditional and currently most common use as lightweight fill. This paper and presentation together are an updated and somewhat more focused assessment of broader 'new millennium' assessments of cellular geosynthetics in general that have been performed by the author in recent years (Horvath 1999a, 1999b, 2001a, 2001b).

The overall motivation for this particular invited paper and presentation is the observation by the author that despite the very impressive growth in cellular geosynthetics technology in recent years the average user of that technology is still only aware of a relatively small fraction of the existing body of knowledge. With specific regard to EPS geofoam, there are many geosynthetic functions that products made from EPS can provide in addition to the well known and widely used lightweight fill. In most cases, these additional functions:

- have been known and already used to some extent in practice, in some case for more than 40 years; and
- represent functions not available with other geosynthetic product.

Thus these additional functions are very attractive in principle to both design professionals and end users alike as they represent potential construction alternatives and problem solutions that are simultaneously both unique and proven. As such, they offer the potential for new solutions, available now, to situations encountered in practice. However despite all their attractions experience indicates that these additional functions are significantly underutilized in practice. The clear reason for this appears to be lack of knowledge, something that this paper and accompanying presentation hope to alleviate in some small way.

2.0 FUNCTIONAL APPLICATIONS OF EPS GEOFOAM

2.1 Introduction

'Design by function' is the basic precept that should be applied whenever the use of geosynthetics is considered. This simply means that before specific geosynthetic materials and products are selected for use on a specific project the functions (roles) that are to be provided by the geosynthetics must be clearly identified. This concept, so simple and rational in its content

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yet so often overlooked in practice, can be expanded to include any special design considerations unique to the project.

Applying the design-by-function concept when designing with EPS geofoam thus requires knowledge of the geosynthetic functions that EPS can provide. The key overall fact to keep in mind in this regard is that, with few exceptions, EPS geofoam can provide functions that are not provided by any other type of geosynthetic. This fact together with the worldwide availability and relatively low cost of EPS compared to other synthetic construction materials explains why it is the geofoam material of choice worldwide and in most geofoam applications.

2.2 Overview of Functions

The geosynthetic functions that can be provided by EPS-geofoam products have been discussed in detail in numerous publications with Horvath (1995) still the most complete English-language publication on the subject. For reference purposes, the EPS-geofoam functions are listed here in the approximate chronological order in which they were identified or developed:

- thermal insulation;
- lightweight fill;
- drainage (not a function itself but the collective, synergistic combination of two distinct but complementary functions, transmission and filtration, with the EPS geofoam always providing the transmission component);
- noise and small-amplitude-vibration damping;
- compressible inclusion; and
- structural/miscellaneous.

It is important to note that although this functional list has remained static for some years now the specific applications within each function continue to evolve as does the technical knowledge and project experience about specific functions and applications.

2.3 Underutilized Functions

With the exception of the lightweight fill function (and to some extent the thermal insulation function as well), all of the above functions can be considered underutilized in current practice, at least in most countries and including the U.S.A. Even with the well known lightweight fill function and somewhat known thermal insulation function, users are often unaware of the full breadth of their applications.

In consideration of these facts it is clear that there is much that could and should be done to educate users about all of these functions and their full breadth of potential applications. However, given the practical limitations of what can be accomplished within the time and space

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constraints of this seminar, the remainder of this paper will focus on the compressible inclusion function. This is because all available indications are that this function has the potential to be the most significant and widely used of all EPS-geofam functions, eclipsing even the well established use of EPS as a lightweight fill material.

3.0 THE COMPRESSIBLE INCLUSION FUNCTION

3.1 Background

The analysis or design of any geotechnical structure is fundamentally based on the need to prevent failure (the *limit state*) in the broadest sense of the word (i.e. loss of function) by satisfying the equation:

$$\text{resistance (capacity) of the structure} > \text{loads (demand) applied to the structure} \quad (1)$$

To the extent capacity exceeds demand constitutes 'safety' incorporated into the structure.

Historically, civil engineers have satisfied Eq. 1 by increasing the left-hand (resistance) side of the equation. The loads, generally dictated by nature either directly (wind, earthquake) or indirectly (gravity acting on the occupants of the structure as well as the structure itself), are simply accepted as is without further thought and material is added to the structure so that Eq. 1 is satisfied from both a stiffness (*serviceability limit state*, SLS) and strength (*ultimate limit state*, ULS) perspective.

There are, however, other ways to satisfy Eq. 1. The right-hand (load) side of the equation can be reduced, or there can be some combination of load reduction and resistance increase. In general, the concept of load reduction works particularly well for geotechnical structures because in many geotechnical problem categories, especially those involving earth retaining structures or earthworks, a predominant portion of the design loads come from the mass of the structure and surrounding soil under gravity or seismic acceleration. Because mass can be modified, even though the natural phenomena accelerating that mass cannot, means that the end result (force, which, per Newton, equals mass times acceleration) can be modified.

3.2 Earth Retaining Structure Load Reduction Alternatives

Although this paper will address a broad range of applications of the compressible inclusion function, experience indicates that the application of broadest appeal is with earth retaining structures, especially in transportation applications (Horvath 2004c). In consideration of this, it is useful to address some issues related to such structures before proceeding further with the more general discussion.

There are two broad alternatives for reducing loads on earth retaining structures:

- use a 'lightweight' (low density/low unit weight) material for some portion of the fill/backfill behind the structure or
- use a compressible inclusion to induce or allow 'controlled yielding' within a normal soil fill/backfill.

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A discussion of the former alternative is not included here as sufficient publications on the subject already exist, with Horvath (1995) providing the most comprehensive introduction to the subject. The present discussion will be limited to the latter alternative.

3.3 The Concept of Controlled Yielding

In this context, the term "yielding" is synonymous with displacement. Thus the term 'controlled displacement' is arguably better to use than 'controlled yielding' as it more clearly states what is happening. However the term controlled yielding has been used in the literature for some time now and is thus better to use for the sake of continuity.

Controlled yielding in its broadest definition is the generic, intentional use of a relatively thin layer or zone of special material (referred to as the compressible inclusion) between the ground and a rigid and/or non-yielding structure that would normally be in direct contact with the ground. The primary distinguishing feature of the compressible inclusion material is that it is relatively much more compressible than any of the other materials that surround it.

The primary function of the compressible inclusion is to sacrificially compress and allow the ground to displace adjacent to a structure in a situation where ground displacement would otherwise be restricted or even prevented entirely due to the constraints imposed on it by the structure. The benefit of this displacement is a reduction in earth forces acting on the structure. This can translate into reduced costs for new construction or improved performance (i.e. a greater margin of safety in the context of Eq. 1) for existing structures. The fact that compressible inclusions can be retroactively installed with many types of existing structures is an important practical benefit to be noted.

3.4 Materials to Induce Controlled Yielding

There are numerous potential applications of controlled yielding and some have been exploited since at least the early 20th century. For example, bales of hay or straw have long been used over underground conduits (pipes, culverts and small-diameter tunnels) to induce vertical arching and reduce the vertical forces acting on them (Spangler and Handy 1982). In recent years, various types of cardboard 'void formers' have been used in a variety of applications beneath structural slabs and behind earth retaining structures. However, what makes modern application of the controlled yielding concept using geosynthetics different than such earlier practices is that geosynthetic materials can be selected to be both durable and predictable in their behavior (organic materials such as hay, straw or cardboard are neither). As a result, the use of geosynthetic compressible inclusions is what has turned an interesting but heretofore uncontrollable and unpredictable phenomenon (and thus something many have been reluctant to use in routine practice) into one that can be readily and reliably analyzed, and is thus consistent with modern geotechnical engineering and construction practice.

In particular, it was the evolution of block-molded expanded polystyrene during the latter half of the 20th century that provided the basic durable, predictable material which made greater use of the controlled yielding concept practicable. In recent years, additional materials research has led to the development of what is called resilient or elasticized block-molded expanded polystyrene which is a more cost-effective material to use in most compressible inclusion applications. There are also various related polystyrene materials such as the inherently high-

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porosity glued polystyrene porous block that are used in conjunction with solid expanded polystyrene (either normal or resilient) when drainage is also desired. A complete discussion of the EPS family of compressible inclusion materials and products is beyond the scope of this paper. A broad overview can be found in Horvath (1995) with a more focused introduction in Horvath (1996; republished in Horvath 1998a).

4.0 APPLICATIONS TO EARTH RETAINING STRUCTURES

4.1 Introduction

As noted previously, an assessment of compressible inclusion applications identified to date indicates that those related to earth retaining structures have the greatest potential for routine use due to the broad occurrence of such structures in all geographic areas and geologic settings. There are two broad categories of controlled yielding application that have been identified for use with earth-retaining structures:

- the *Reduced Earth Pressure (REP) Concept* and
- the *Zero Earth Pressure (ZEP) Concept*.

Each of these application concepts has been studied to varying extents since at least the early 1980s. Most of these studies involved either small-scale model testing under 1g conditions or numerical analyses using a finite-element solution of a continuum (other numerical solution techniques may have also been used but the author is not aware of any published references for same). There has been relatively little published data for full-scale testing or case history observations to date. The author is not aware of any published studies involving multi-g (centrifugal) testing of small-scale models although the author has received anecdotal information about such testing.

Collectively, these studies have been both necessary and useful for exploring the basic behavior of both the REP and ZEP concepts to varying levels of detail. However, it is well appreciated that for the concept of controlled yielding to be used routinely in practice analytical methodologies simpler than complex, time-consuming physical modeling or numerical analyses must be developed. Therefore, this paper will focus on the development of simple models and solutions intended for use in routine practice as opposed to fundamental research.

4.2 The Reduced Earth Pressure (REP) Concept

4.2.1 Concept Overview

This type of application is illustrated conceptually in Figure 1 and can be considered the basic, fundamental application of controlled yielding with an earth retaining structure. Note that the earth retaining structure shown is conceptual in nature and should not be viewed as only a gravity retaining wall. It can be any type of relatively rigid and/or non-yielding structure such as a retaining wall, bridge abutment/wingwall, below-grade (basement) wall of a building, or navigational lock to name a few of the more common ones.

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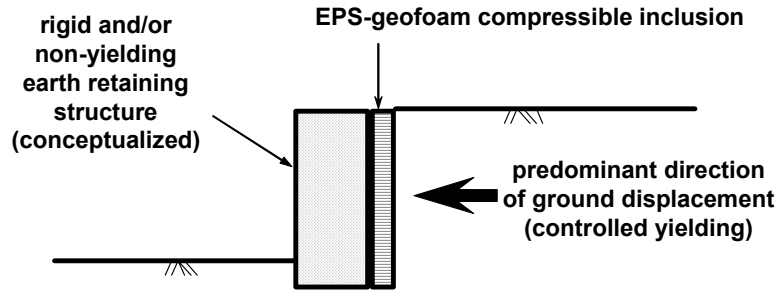


Fig. 1. Conceptual Illustration of the REP Concept

In most REP applications, the primary geotechnical design variable of interest is the compressive stiffness of the compressible inclusion in the primary direction of its compression (horizontal in Figure 1). This stiffness is defined as the operative Young's modulus of the compressible inclusion material, E_{ci} , divided by its thickness, t_{ci} . "Operative" in this case means as measured or otherwise determined on either a tangent- or secant-modulus basis at a stress level and duration of loading that is consistent with a project-specific application.

Recent research has demonstrated that it is useful to define a new dimensionless parameter, λ , called the 'normalized compressible inclusion stiffness' (Horvath 2000). This parameter is defined as

$$\lambda = \frac{E_{ci} \cdot H}{t_{ci} \cdot p_{atm}} \quad (2)$$

where H is the 'geotechnical' height of the earth retaining structure (the vertical distance from the base of the wall to where the retained soil contacts the back of the wall) and is assumed to be the same as the height of the compressible inclusion; p_{atm} is atmospheric pressure (used solely as a non-dimensionalization parameter); and the other terms are as defined previously.

Any consistent set of units may be used in Eq. 2 so as to produce a dimensionless value of λ . For reference purposes, 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. Quantitatively, the smaller the value of λ the more compressible the inclusion is.

Regardless of the specific application, the basic manner in which the compressible inclusion behaves and is designed is illustrated in Figure 2. The ground has some force-versus-tensile-displacement relationship that is dictated by the site-specific ground conditions and application. In general, the greater the ground displacement in extension the smaller the force the ground will exert on the earth retaining structure. Note that the ground force may or may not go to zero in the limit of infinite displacement (that will depend on the specific category of application as discussed in detail in subsequent sections of this paper) as indicated by the range in possible behaviors depicted in this figure. On the other hand, the compressible inclusion has a reciprocal behavior in that the more it displaces in compression the greater the force that is required to achieve this compression.

For convenience, both the ground and compressible inclusion can each be visualized as a spring (note, however, that this does not imply that they behave as a Winkler subgrade) and the design process is simply to match the stiffnesses of the ground and compressible inclusion

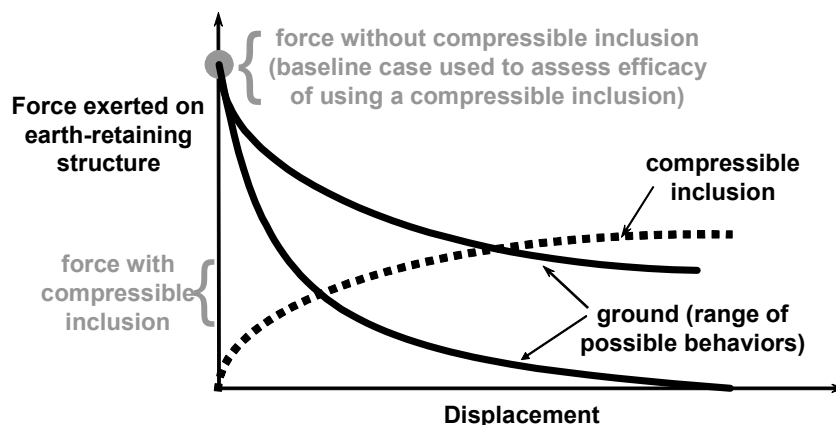


Fig. 2. Qualitative Behavior and Solution of the REP Concept

'springs' to produce a reduced design force on the earth retaining structure (the magnitude of this reduced force is where the force-versus-displacement curves of the ground and compressible inclusion intersect). Note again that depending on the specific category of application and whether or not the ground force goes to zero in the limit of infinite displacement, there may or may not be a unique solution, i.e. a unique required thickness of the compressible inclusion to achieve some minimum force on the structure.

Within the context of this general behavior, there are several distinctly different categories of applications. Each is summarized in the following sections.

4.2.2. Applications Involving Shear Strength Mobilization

This was the first application of the REP concept that was identified and is arguably the most common. It is a direct outgrowth of the previously noted use of unengineered compressible inclusions above underground conduits.

In this application, the desire is to simply mobilize the inherent shear strength of the retained soil by allowing sufficient ground displacement so that the assumed classical active earth pressure state develops in situations where design for the at-rest (or larger) earth pressure state would normally be appropriate due to the non-yielding nature of the earth retaining structure. Note that in this type of application and with reference to Figure 2 the force exerted by the ground (soil) will always plateau at some non-zero magnitude after a certain minimum magnitude of lateral displacement, Δ_a , of the soil mass (whether or not this force first dips to some minimum as the peak shear strength is mobilized and then rebounds slightly before leveling off as the soil dilates and the constant-volume condition (critical state) is reached is a behavioral nuance that is neglected here for simplicity).

Historically, Δ_a has usually been expressed in various tabulations (see, for example, Clough and Duncan (1991)) as a dimensionless ratio, Δ_a/H , where H is again the geotechnical height of the structure as defined previously. Because, theoretically at least, the earth force reaches and remains at this limiting minimum value (the active state) regardless of any displacement beyond the threshold Δ_a value this is an example of an application where there is a unique solution in terms of the required thickness of the compressible inclusion. This is because a thicker inclusion

would provide no theoretical benefit as the soil would exert the same earth force on the structure even under additional displacement.

For simplicity in analysis and design of the earth retaining structure, it has generally been assumed in practice to date that the distribution of lateral earth pressures achieved using a compressible inclusion in this manner will follow a classical triangular distribution. However, numerical analyses (Horvath 1991, Murphy 1997) as well as observed results from both small-scale, 1-g model tests and actual full-scale project applications (Partos and Kazaniwsky 1987) consistently indicate a curved, roughly parabolic distribution as shown by the curved labeled "REP" in Figure 3. The traditional triangular distributions of active and at-rest lateral earth pressures are shown for comparison. Such a result is not surprising as the use of the REP concept behind an earth retaining structure where shear strength mobilization of the retained soil is the operative mechanism is, in essence, inducing horizontal arching within the soil. Such curved distributions of lateral earth pressures are completely consistent with theoretical results for arching theory when applied in the horizontal direction against earth retaining structures (Handy 1985, Harrop-Williams 1989).

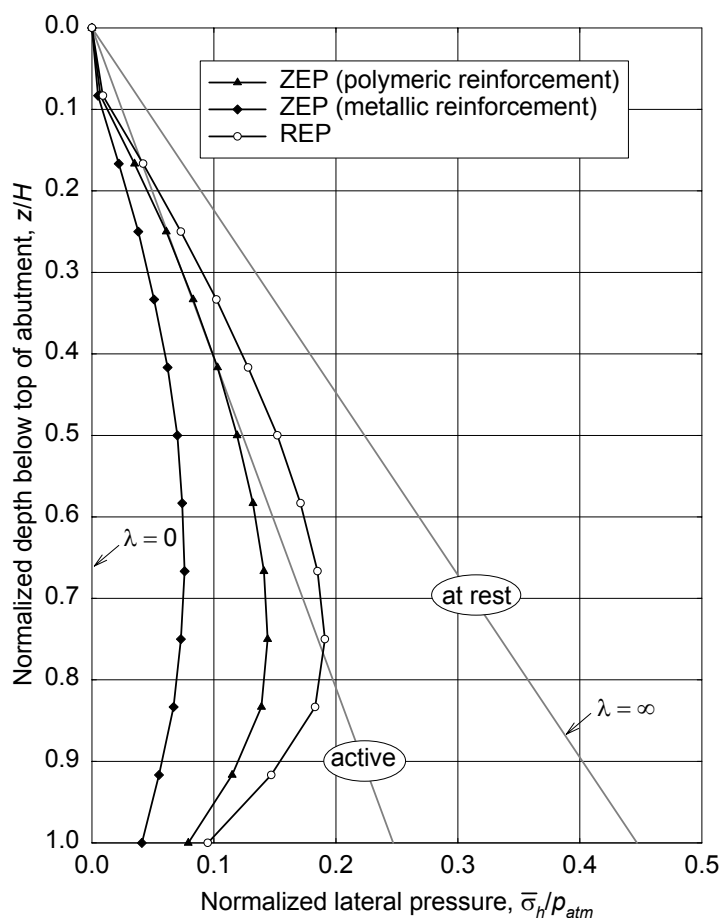


Fig. 3. Comparison of Lateral Earth Pressure Distributions (Horvath 2000)

In developing a simplified design methodology for this category of application of the REP concept, the author has, over time, come to the conclusion that the resultant force, not pressure,

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should be used as the primary parameter in any simplified analytical model for use in routine practice. Where this calculated resultant force is placed on the structure and/or how this force is distributed as a stress along the back of the structure for various geotechnical and structural calculations is then a matter of professional judgment.

As discussed in detail in Horvath (2000), the development of a simplified solution for the REP concept for the fundamental application where shear strength mobilization is sought has gone through several evolutionary changes since it was first proposed by Partos and Kazaniwsky (1987). The current version presented in Horvath (2000) is

$$t_{ci} = \frac{E_{ci} \cdot (\Delta_a / H)}{0.75 \cdot K_a \cdot \cos \delta \cdot \gamma_t} \quad (3)$$

where K_a is the active earth pressure coefficient obtained using either Coulomb or some 'exact' (e.g. log-spiral) theory (but never Rankine which is theoretically incorrect to use here); δ is the friction angle between the retained soil and the compressible inclusion; γ_t is the total unit weight of the retained soil; and the remaining terms are as defined previously. Again, note that this is an application where there is always a unique solution to the problem (minimum required thickness of compressible inclusion, t_{ci} , to achieve the desired result) although the magnitude of t_{ci} will always be project specific. Note, however, that using a greater thickness of compressible inclusion than that indicated by Eq. 3 is acceptable. As discussed by Partos and Kazaniwsky (1987) they exercised engineering judgment and intentionally used a significantly greater thickness of material than both material testing and their calculations indicated was necessary. Their decision was certainly understandable given the unique (at the time) use of EPS geofoam as a compressible inclusion.

4.2.3 Accommodating Structure-Induced Movement

One of the often overlooked aspects of earth retaining structures is that they may undergo displacements of a broadly horizontal nature due to combinations of translation and rotation initiated by the structure itself and not as a result of the structure reacting to earth loads. This is usually the result of the earth retaining structure itself being subjected to thermal changes (e.g. water and wastewater treatment facilities (England 1994) and navigational locks (Clough and Duncan 1972)) or being physically connected to some structure that moves (e.g. integral-abutment and jointless bridges (Horvath 2000, 2005)).

Whatever the specific origin, such behavior can lead to relatively large lateral earth pressures, i.e. well in excess of the at-rest state and tending toward the passive, whenever the causal mechanism (which is usually the seasonal rise in atmospheric temperature) pushes the earth retaining structure into the adjacent retained soil. This, in turn, can lead to structural failure of the earth retaining structure unless it has been designed to withstand these relatively large lateral earth pressures (Diviney 1990). It is generally much more economical to use a compressible inclusion to accommodate structure displacement with a much reduced increase in lateral earth pressures than to design to withstand these pressures.

A single, generic, simplified design methodology for EPS-geofoam compressible inclusions used in these situations has not yet been developed and may prove challenging given the

diversity and complexity of this particular type of application. However, it may prove possible to develop a simplified design procedure for each specific problem category, e.g. integral-abutment/jointless bridges. Research is currently underway along these lines.

4.2.4 Accommodating Volume Change of Earth Materials

An application of considerable interest in certain geologic and geographic settings that are found worldwide involves situations where the ground retained by an earth retaining structure is susceptible to significant volume changes simply due to environmental conditions, most commonly changes in water content due to both natural weather patterns and human activities. This applies primarily to the well known problem of expansive or swelling soils although expansive rocks and freezing soil are other potential applications. Wherever possible, either expansive soils are not used as backfill/fill behind an earth retaining structure or, conversely, an earth retaining structure is not built where such soils are the only ones available for use. This is broadly for the same reason related to economics as described in the preceding section for structure-induced movement, i.e. one could always design and build an earth retaining structure that would withstand lateral earth pressures from expansive ground but would it be worth it?

EPS-geofoam compressible inclusions offer the heretofore unavailable potential for a technically acceptable and cost-effective alternative that would allow routine use of expansive soils as backfill/fill behind earth-retaining structures as well as the construction of such structures in areas where they were previously avoided. There has been some preliminary analytical work that supports this opinion (Aytekin 1997). What is lacking at the present time is a relatively simple analytical methodology that will allow this concept to be applied site specifically on routine projects without having to resort to complex and costly numerical analyses. Development of such a methodology should be considered a high priority given the worldwide occurrence of expansive soils and the economic losses they cause.

One thing to keep in mind with regard to using a compressible inclusion to reduce lateral earth pressures from expansive soil/rock or freezing soil is that, with reference to Figure 2, the ground force in this case will always go to zero at some finite magnitude of displacement (although it would require a compressible inclusion of zero stiffness to achieve this, something that is not practically possible). This means that there is never a unique thickness of the compressible inclusion to use in such applications as there is when shear strength mobilization is involved. Rather, there is a range of thicknesses that is bounded by practical limits on available EPS-geofoam products and thicknesses of compressible inclusion that can be reasonably used. In practice, a compressible inclusion thickness is selected that provides the best overall economy considering the costs of both the earth retaining structure and compressible inclusion. This is because the cost of the earth retaining structure decreases as the thickness (and thus the cost) of the compressible inclusion increases. The optimum cost point is where the combined cost of the two components reaches a minimum.

It is worth noting that there are other important uses of EPS-geofoam compressible inclusions with expansive ground in addition to earth retaining structures. These additional applications are discussed subsequently in Section 5.0.

4.3 The Zero Earth Pressure (ZEP) Concept

4.3.1 Overview

This application concept evolved from the REP concept and is illustrated in Figure 4 (unlabeled elements are the same as in Figure 1). The unique additional feature of the ZEP concept is the embedment of multiple layers of geosynthetic tensile reinforcement (metallic or polymeric) within the retained soil. In essence, a more or less self-stable mechanically stabilized earth (MSE) mass is constructed behind the primary earth retaining structure.

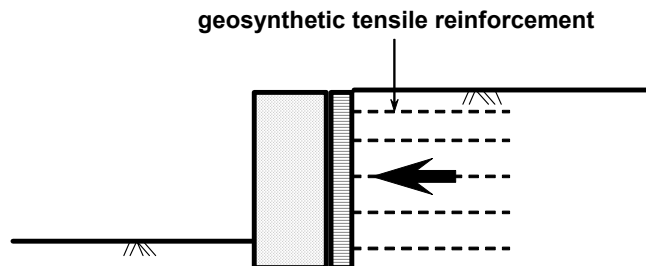


Fig. 4. Conceptual Illustration of the ZEP Concept

With regard to selecting the appropriate stiffness of the compressible inclusion for ZEP applications, the same basic procedure as discussed previously for the REP concept and illustrated qualitatively in Figure 2 applies. However a significant difference with respect to the application of Figure 2 to the ZEP concept is that in all cases and for all types of soil the ground force in the figure will always become zero at some finite magnitude of displacement. This is because at some magnitude of horizontal displacement the geosynthetic tensile reinforcement becomes fully activated and completely capable of supporting the ground (this presumes adequate design of the reinforcement for both pullout and rupture). This behavior is what gave the ZEP concept its name, i.e. with reference to Figure 4 it is, in concept, always possible to create a self-supporting MSE mass so that zero horizontal stress is transmitted to the primary earth retaining structure.

However, in reality there will always be some small lateral earth pressure that will be transmitted to the primary earth retaining structure simply because a zero-stiffness compressible inclusion cannot practically be constructed so it is never quite possible to reach the zero-force point in Figure 2.

4.3.2 Combined Shear Strength Mobilization and Tensile Reinforcement Activation

The enormous potential of the ZEP concept has barely been explored in research or exploited in practice to date. However, it is likely that in most practical applications this concept would be used to reduce the earth force to some magnitude smaller than the active state which is what can be nominally achieved using a compressible inclusion alone (i.e. the REP concept). The specific level of earth-force reduction would depend on a project-specific technical and economic assessment. In any event, the reduction in the lateral earth force would accrue from

simultaneously and synergistically mobilizing the inherent shear strength of the soil as well as activating some portion of the tensile capacity of the geosynthetic reinforcement.

The type of lateral earth pressure reduction that can be achieved using the ZEP concept in this manner is illustrated in Figure 3 for the same problem that was analyzed previously using the REP concept. Note that the same roughly parabolic distributions of lateral earth pressures are typically achieved using the ZEP concept as was noted previously for the REP concept. Note also that this figure is not intended to imply the superiority of one type of geosynthetic tensile reinforcement over another. It simply shows that, for the same compressible inclusion stiffness, λ , the lateral earth pressures are sensitive to the relative stiffness of the tensile reinforcement used (the metallic reinforcements modeled in this specific example were simply overall stiffer than the polymeric reinforcements).

With regard to developing simplified analysis and design methods, work with the ZEP concept is much less advanced compared to the REP concept even though researchers have been investigating both concepts for about the same length of time (since about the early 1980s). In the author's opinion, this is because of the complexity of having to define the horizontal 'spring' stiffness of the reinforced retained-soil mass which replaces the 'spring' stiffness of the ground alone in Figure 2. The root cause of this complexity derives from the simple fact that MSE design methods developed to date for use in routine practice are all strength based as opposed to displacement based. Consequently horizontal displacements of MSE masses under service load conditions are not calculated or even calculatable on a routine basis. In addition, the author is not aware of any relatively simple methodology for determining the horizontal-force-versus-horizontal-displacement relationship for a MSE mass that has been developed for any purpose. This would require the use of relatively complex and time-consuming, project-specific numerical solutions of continua which violates the objective of having a relatively simple analytical methodology similar to that outlined in Section 4.2.2 for the REP concept.

Nevertheless, initial development and postulation of a simplified design procedure for the ZEP concept was made in Horvath (1997; republished in Horvath 1998b). It was superseded by a completely revised methodology first presented in Horvath (2000). This revised methodology is too lengthy to reproduce here but is easily solved by manual calculation, a desired goal. However limited comparison of results obtained using it against more rigorous numerical results show this current simplified method to be quite conservative to the point of being disappointing and questionable for suggested use in routine practice. Although the basic concept on which this methodology is based is believed to be sound (it essentially mathematizes the concept illustrated in Figure 2) the current specific aspects of the model clearly require further improvement. All evidence indicates that the most promising area in which to effect improvement is to develop a better way to estimate the horizontal stiffness of the retained MSE mass. Research into this aspect is currently in progress.

4.3.3 Accommodating Structure-Induced Movement

This application is identical to that discussed previously under the REP concept (Section 4.2.3). The primary benefit of using the ZEP as opposed to REP concept with a displacing earth retaining structure such as an integral-abutment or jointless bridge is for the 'winter' case when cooler temperatures cause the structure to move away from the retained soil (there is, theoretically, no difference between the REP and ZEP concepts for the 'summer' case when the

structure moves into the soil). Although the ZEP concept offers better reduction in lateral earth pressures compared to the REP concept for the winter case (which is of no practical benefit), the much more significant difference is the fact that the reinforced soil mass that is part of the ZEP concept significantly restricts soil settlement adjacent to the earth retaining structure (the REP concept does nothing to restrict this settlement and may actually make it worse). This consideration is important when dealing with structures such as integral-abutment/jointless bridges in order to prevent or at least limit development of the problematic 'bump at the end of the bridge' as well as structural failure of ancillary bridge components such as approach slabs (Horvath 2000, 2005). Thus the use of the ZEP as opposed to the REP concept with such structures offers considerable technical benefit and long-term cost savings.

As with the REP concept (Section 4.2.3), there is as yet no simplified analytical methodology for applying the ZEP concept to problems involving structures such as integral-abutment bridges that move as a result of external mechanisms independent of the ground. Realistically there is considerable research that will have to be done before such a methodology could become a reality.

5.0 OTHER APPLICATIONS OF THE COMPRESSIBLE INCLUSION CONCEPT

5.1 Introduction

The preceding section focused intentionally on applications of the compressible inclusion function to situations where the inclusion is aligned more or less vertically in a 'chimney' orientation so as to induce or accommodate displacements in a more or less horizontal direction. Such applications are believed to have universal appeal in a wide variety of applications in every geographic area, geologic setting, and climatic environment which is why this paper and accompanying presentation focused on them. In fact it can be argued that virtually every rigid and/or non-yielding earth retaining structure, whether a simple basement wall of a single-family house, bridge abutment, or complex navigational lock, could benefit technically and economically from the use of an EPS-geofoam compressible inclusion, especially when the multifunctional benefits are factored in (this is discussed subsequently in Section 6.0).

However, as summarized in Horvath (2001a) there has been technically successful and cost-effective use of EPS geofoam for the compressible inclusion function in other types of the applications where the compressible inclusion is oriented more or less horizontally to induce or accommodate ground displacements in a more or less vertical direction. There are at least two distinct categories for this application that have been identified and used to date, and they are discussed in the following sections. Although each of these applications has more limited potential usage compared to the universal use of compressible inclusions with earth retaining structures, each is nonetheless potentially significant within certain combinations of geologic, geographic and climatic conditions that can be found worldwide. As such, each has the potential for significant use and impact within an appropriate setting.

5.2 Accommodating Volume Change of Earth Materials Beneath Structural Slabs

5.2.1 Overview

This application is broadly similar in concept to that discussed previously in Section 4.2.4 for earth retaining structures and is illustrated in Figure 5. As in previous figures, the large arrow indicates the primary direction of ground movement the compressible inclusion is designed to accommodate.

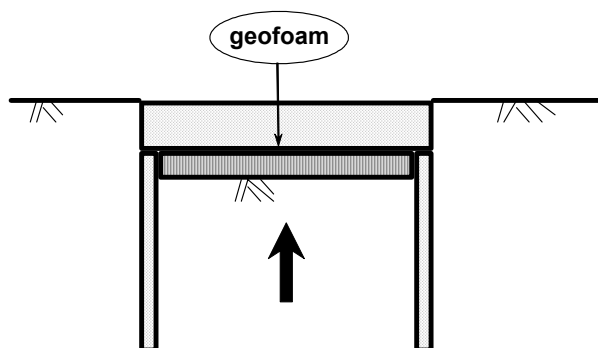


Fig. 5. REP Concept: Structural Slabs in Expansive Ground

The system under consideration here consists of a structural slab supported on deep foundations, usually some type of drilled foundation element (pile or shaft) nowadays. Such a slab is designed to span between the deep-foundation elements (generally using a system of grade beams which are not shown in Figure 5 for simplicity) and not rely on any intermediate support from the underlying ground as would be the case with a slab-on-grade ('floating slab') type of design. In fact the underlying ground, with its ability to expand upward in the long term and exert a very large stress on the underside of the slab, is the root cause of the problem requiring the use of a compressible inclusion in the first place. Note that this is significantly different than for a slab-on-grade type of design where the underlying subgrade is the sole source of beneficial support.

Ideally, of course, it would be desirable to construct the structural slab shown in Figure 5 some distance above the potentially expansive underlying ground so that during the design life of the slab the underlying subgrade never expands enough to come into contact with the slab. However constructability considerations make this practically impossible as, of necessity, the underlying ground is a de facto part of the formwork for the cast-in-place concreting used to construct the structural slab and grade beam system. Thus the compressible inclusion is used between the slab and subgrade as a pragmatic compromise. The inclusion allows concreting to be readily accomplished during construction yet serves as a crushable zone of material during the life of the slab as the underlying subgrade expands. Note, however, that in this type of application the compressible inclusion must serve dual purposes which, as it turns out, place competing and contradictory demands on the compressible inclusion product. This turns out to be the single most important design consideration for this type of application and is discussed in detail subsequently in Section 5.2.3.

It is worth noting that in areas with expansive ground the type of compressible inclusion application shown in Figure 5 is likely to be vastly more common and useful in practice

compared to the companion application discussed in Section 4.2.4 for earth retaining structures. The reason is that it is generally possible to avoid or at least minimize the use of earth retaining structures in areas with expansive soil or rock conditions (or use non-expansive earth materials imported to the project site as backfill/fill). However it is not possible to avoid building structures above expansive ground or to completely replace such materials with imported non-expansive soils. Experience in practice to date corroborates this hypothesis. Although the use of compressible inclusions behind earth retaining structures in expansive ground is still very much in the early stages of development as discussed previously in Section 4.2.4 the use of compressible inclusions beneath structures as shown in Figure 5 is a widely accepted and relatively mature technology worldwide. What is changing, however, is the substitution of EPS geofoam as the material of choice compared to cardboard 'void formers' as has been used exclusively in the past. EPS geofoam offers superior construction and post-construction performance which explains the ongoing shift in material usage in this application.

5.2.2 Analysis and Design Methods

In view of the fact that the use of EPS-geofoam compressible inclusions as shown in Figure 5 is rapidly becoming the preferred product in those geographic areas where expansive ground is an important design consideration, it is no surprise that analysis and design methods for use in routine practice are reasonably well established. The two approaches the author has seen used in practice (there may well be others) can be broadly referred to as the 'exact' and 'simplified' methods. However both are relatively easy to use, can be solved manually if desired, and are based on the same site characterization of the site-specific ground conditions.

The design process begins by defining the limiting cases of:

- fully-confined condition in which there is no ground displacement and swelling pressures exerted by the ground are the maximum that can occur. Quantifying this case is always desirable in practice to provide a baseline case for assessing the upward pressures that would act on the structural slab if no compressible inclusion were used; and
- free-swell condition in which there is no swelling pressure and upward displacement (heave) of the ground surface is unrestricted so is the maximum that can occur.

Once these limiting cases have been determined, the so-called exact method uses any one of several analytical methods for relating swelling pressures and heave that have been developed for expansive ground. Such analytical methods are used to develop additional swelling-pressure-versus-heave data points between the two limiting cases. In the past, the author has used a theoretically rigorous solution presented by Fredlund and Rahardjo (1993) for generating these additional, intermediate data points. A curve is then fitted experimentally through all the data points and plotted together with the stress-compressive displacement curve for the compressible inclusion as shown in Figure 6. Note that this figure is a version of Figure 2 modified for this particular application. The upward pressure for which the structural slab is designed is where these two curves intersect. Note that this is another one of those compressible inclusion applications for which there is no unique answer, i.e. there is no unique thickness of the geofoam layer. Rather there is an infinite range of possible thicknesses that could be used. The thickness

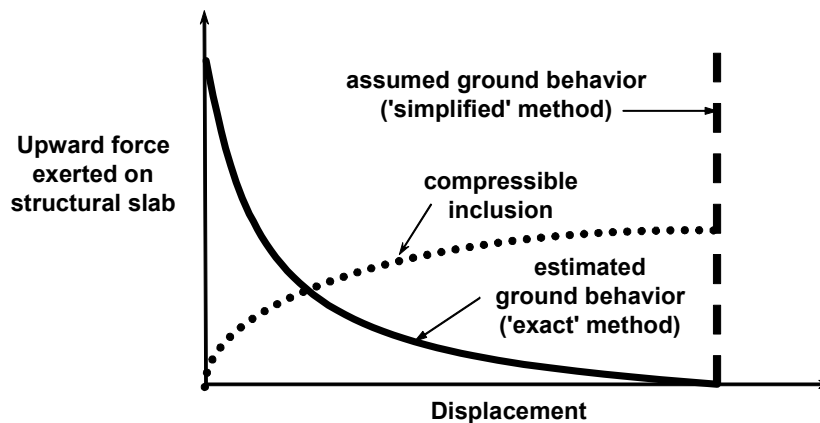


Fig. 6. Analysis Methods for Structural Slabs

chosen for a specific project is based on a project-specific assessment of economics (slab costs decrease as inclusion thickness increases) plus practical considerations as to the maximum thickness of an inclusion that can be physically accommodated in a given application.

The so-called simplified method has been widely used in practice to date (in Canada and the U.K. at least where the use of EPS-geofoam compressible inclusions for this application is now routine) and ignores the relationship between swelling pressure and heave as depicted by the solid curve in Figure 6. Rather the results from a free-swell test or analysis are simply projected vertically as shown by the dashed line in Figure 6. Where this dashed line intersects the stress-compressive displacement curve of the compressible inclusion provides the upward design pressure on the underside of the structural slab. Note that this simplified method will always produce a larger and more conservative slab design pressure compared the exact method described above. In view of the fact that the simplified method always produces conservative results and is extremely easy to use in practice (it lends itself to being reduced to simple tables or charts in manufacturer's product literature for example) experience has indicated that it is the current method of choice in practice.

5.2.3 Material and Product Selection

The use of a compressible inclusion for the application discussed in this section places an unusual demand on the material and product selected for use. This demand is unique to this particular application when compared to the many other uses of compressible inclusions. Referring to Figure 5 and as alluded to previously in Section 5.2.1, the compressible inclusion has to simultaneously satisfy two competing and contradictory requirements. On one hand, the inclusion should be as compressible as possible after construction to minimize the upward pressure transferred to the underside of the structural slab during the design life of the structure. On the other hand, the inclusion must be sufficiently stiff so as to resist the foot traffic of construction personnel and dead load of the fluid concrete during construction with minimal compression so that the curing slab does not sag. The inclusion must also be sufficiently durable during construction so as to survive the possibility of wetting due to precipitation or some construction activity. This last consideration is one reason why cardboard, which softens and

crushes immediately upon wetting, has fallen out of favor as a material used in this application once EPS-geofoam products became available commercially. These competing needs have led to the development of innovative geofoam products that are intended solely for this application.

5.2.4 Exclusions

It is important to emphasize that the application discussed in this section only applies to structural slabs supported on deep foundations that extend below the active zone of the expansive soil or rock. There is no known benefit to using a compressible inclusion beneath a slab-on-grade constructed on expansive ground. This point is emphasized here as it is not uncommon to find slab-on-grade construction used for economic reasons in areas with expansive ground. Confusion has occurred in the past as to the efficacy of using a compressible inclusion with such construction.

5.3 Shear Strength Mobilization Over Underground Conduits

5.3.1 Overview

This application is illustrated in Figure 7 and currently available information indicates this may have been the very first use of the compressible inclusion concept, dating back at least to the earliest decades of the 20th century when bales of hay and straw were used as the compressible inclusion material (Spangler and Handy 1982). The basis of this application derives from the fact that the vertical force acting on the crown (if curved) or roof slab (if flat) of an underground conduit can vary over a relatively large range depending on the relative downward vertical displacement between the top of the conduit and adjacent ground. Experience indicates that this vertical force can easily exceed the vertical overburden stress. If the conduit has not been designed for such a force it can lead to structural failure of the conduit. Conversely, to design for such a force carries with it an economic penalty in terms of conduit cost. As a result, there was extensive research in the early 20th century to develop analytical methods for reliably determining the vertical force at the top of an underground conduit and, as a corollary, develop design strategies to ensure that this force could be minimized if desired in any type of application by implementing certain design details. In most cases these load-reduction details included the placement of a more-compressible zone of material directly above the top of the conduit.

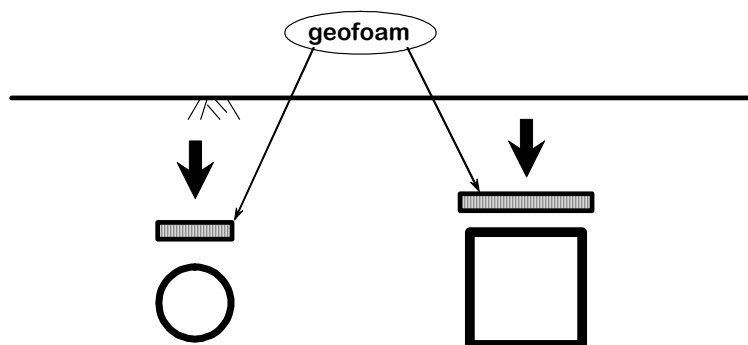


Fig. 7. REP Concept Applied to Underground Conduits

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The conclusions of this research in the earliest days of modern geotechnical engineering have remained broadly valid to the present. What has changed over time is that EPS geofoam has replaced organic materials such as hay and straw as the compressible inclusion material of choice for a number of reasons. Chief among them is the fact that the necessary engineering properties of EPS are predictable, reliable, repeatable, and durable, all traits missing from materials used historically.

5.3.2 Analysis and Design Methods

The current state of practice for using compressible inclusions to reduce design loads on underground conduits is in a state of transition. On one hand, there are extensive theoretical-yet-simple chart solutions, well proven after decades of research and use in practice, that are readily available (Spangler and Handy 1982). However these solutions were developed well before the existence of EPS and its use as a geofoam material so need to be revised and verified as necessary for use with today's materials and products. On the other hand, there has been extensive research and theoretical assessment of the efficacy of EPS geofoam as a compressible inclusion material for this application and even some verification in practice (a fairly complete summary of appropriate references can be found in Horvath (2001a)). However analytical studies to date have generally involved the use of advanced solutions of complex continua using numerical methods such as finite elements. While the use of such numerical methods in engineering practice is not as exotic as it was in the days before the widespread availability of personal computers, the level of effort required is still well beyond that which can be justified on routine projects. Consequently, it is difficult to extrapolate the research performed and experience to date with the use of EPS geofoam with underground conduits into simplified design methods. Thus there is a critical need at present to either modify the traditional solutions as depicted in Spangler and Handy (1982) for use with an engineered compressible inclusion made of EPS geofoam or develop alternative solutions that are reasonably simple for use in routine practice. Until then the full benefit of this application will not be achieved.

6.0 MULTIFUNCTIONALITY

This paper and its accompanying presentation have intentionally focused on the technical aspects of analysis and design using EPS-geofoam products as compressible inclusions. However in the interest of completeness it should be noted that:

- economics always play an important role in addition to technical considerations in any civil engineering design and
- EPS geofoam can provide many other functions in addition to compressible inclusion as was noted in Section 2.2. Some of these additional functions such as thermal insulation and noise/small-amplitude-vibration damping are inherent in EPS as a geofoam material, i.e. they are present whether or not they are recognized, utilized, or even desired in a particular design. Some of these additional functions such as drainage can be easily added during the product manufacturing stage either by making modifications to the EPS itself or combining the EPS with other geosynthetics to create a geocomposite product.

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Combining these two factors, the point made here is that on most projects where EPS geofoam is used primarily as a compressible inclusion its inherent multifunctionality can be used to both technical and economic advantage. Experience to date indicates that thermal insulation and drainage are the additional functions most often used in applications where compressible inclusion is the primary function, especially for applications behind earth retaining structures. However experience also indicates that both design professionals and end users alike have been slow to recognize and take advantage of both the technical and economic benefits of this multifunctionality so this is certainly an aspect requiring greater attention in the future.

7.0 CONCLUSIONS

The use of EPS-geofoam compressible inclusions to reduce earth loads on a wide variety of structures, especially earth retaining structures, has enormous potential. There are few structures that bear on or in the ground that could not benefit in terms of both technical performance and cost reduction from using such materials. In most applications, the required thickness of the compressible inclusion is quite modest, typically less than one foot (300 mm). Thus the cost per unit area (square foot or metre) of compressible inclusion is quite modest. Considering that a drainage capability can easily be incorporated within this thickness (most earth retaining structures require a chimney drain of some type for positive ground-water drainage anyway) the additional cost of using a compressible inclusion is relatively small and easily compensated by the technical and cost benefits that accrue from using it.

At the present time there is a wide variety of commercially available EPS-geofoam products that are appropriate for use where compressible inclusion is the primary desired geosynthetic function. The major suppliers of such products in North America are:

- GeoTech Systems Corporation (www.geosyscorp.com) and
- Plasti-Fab (www.plastifab.com).

Between them they can supply any and all of the compressible inclusion applications described in this paper and its accompanying presentation.

To date the main drawback to greater use of these commercially available EPS-geofoam products in compressible inclusion applications has been a general lack of knowledge about the geosynthetic function of compressible inclusion in general and the existence of these specialty EPS-geofoam products in particular. To a significant extent this broad knowledge gap has been the fault of the EPS manufacturing industry for not doing a better job of informing and educating potential users about this function and these products. One can only hope that the EPS industry will pay more attention to civil engineering and construction markets in the future and do a better job of education which is one of the key elements of the trilogy of technology.

It should also be apparent that there is also a need for fundamental research to develop and/or improve simplified analysis and design methods for several of the specific applications discussed in this paper. Areas where improvement is required to increase use of a specific application have been noted in these discussions. Again, ongoing research to continually push the edge of the technological envelope is another critical component of the trilogy of technology.

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