Controlled Yielding Using Geofoam Compressible Inclusions: The New Frontier in Earth-Retaining Structures

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ABSTRACT: It has been approximately 40 years since Henri Vidal first envisaged and began to develop his proprietary *Terre Armee* (*Reinforced Earth*®) concept using metallic reinforcements. This eventually grew into the broader generic technologies of mechanically stabilized earth (MSE), mechanically stabilized earth walls (MSEWs) and segmental retaining walls (SRWs) using polymeric geogrid and geotextile reinforcements. These geotechnologies have collectively revolutionized earth-retaining structure practice worldwide. In recent years, there has been increasing interest in the use of *compressible inclusions*, composed primarily of expanded polystyrene (EPS) geofoam, to allow *controlled yielding* of a soil mass behind a rigid and/or non-yielding earth-retaining structure. The benefits of doing this are significantly reduced lateral earth pressures acting on the structure which can reduce the overall cost of its construction as well as enhance its performance. This paper outlines the two basic ways in which geofoam compressible inclusions are used with earth-retaining structures: the Reduced-Earth-Pressure (REP) and Zero-Earth-Pressure (ZEP) concepts. Typical applications are also given and there is an emphasis on describing simplified analysis and design methods for both application concepts.

KEY WORDS: earth-retaining structures, controlled yielding, compressible inclusion, geofoam, geosynthetics, cellular geosynthetics, expanded polystyrene

INTRODUCTION

Earth-retaining structures have been constructed by humans for thousands of years and have always been an important part of human culture and civilization. As evidence of this, it is interesting to note that one of the first, if not the first, attempts at developing a methodology to allow for logically civil engineering a geotechnical structure involved an earth-retaining structure. In the 18th century, long before modern soil mechanics was conceived and developed, Coulomb developed his conceptual theory, model and mathematical solution for earth pressures acting on gravity walls.

The importance of earth-retaining structures in society is something that has continued into the 21st century. This is evidenced by the extensive research and development of a wide range of geotechnologies during the last decades of the 20th century that both improved on traditional earth-retaining structures such as rigid retaining walls and introduced entirely new concepts for earth retention such as internal reinforcement (O'Rourke and Jones 1990). In all cases, the goal of this research and development was to develop earth-retaining structures that performed acceptably and predictably while minimizing costs. The newly appreciated need to design for seismic loads in many areas of the world also factored significantly into things.

Of all the recent developments in earth-retention geotechnology, none has been more singularly significant than the work of Henri Vidal. It has been approximately 40 years since he first envisaged and began to develop his proprietary *Terre Armee* (*Reinforced Earth*®) concept using metallic strips for soil reinforcement. His work evolved into the broader generic geotechnology called *mechanically stabilized earth* (MSE) in which a variety of polymeric (plastic) geosynthetics from the geotextile and geogrid geosynthetic product families are used as the synthetic reinforcement. The geotechnologies called *mechanically stabilized earth walls* (MSEWs) and *segmental retaining walls* (SRWs) that evolved from the MSE concept have certainly revolutionized the way in which earth-retaining structures are designed and constructed worldwide.

Improving earth-retention geotechnology is a never-ending process. This paper discusses a geosynthetics-based concept that began during the 1980s, evolved slowly during the 1990s, and now in the 21st century shows the potential to have an even greater impact on earth-retaining structure design and economics than MSE. This new concept of allowing *controlled yielding* within a retained soil mass by using a *compressible inclusion* composed of certain types of geofoam geosynthetic can be used both alone or combined synergistically with MSE to produce end results that neither technology could achieve alone. What is particularly intriguing about geofoam compressible inclusions is that they can easily be designed to be multifunctional which further enhances their economic attraction in routine practice, even in residential construction which is a potentially huge market that has proven stubbornly resistant to using geosynthetics in general. Consequently, it is not unreasonable to consider the concept of using geofoam compressible inclusions as part of an earth-retention system a truly new frontier in earth-retaining structure technology that has the potential to exceed the impact that MSE has had on changing the way in which earth-retaining structures are designed and built.

BACKGROUND

The analysis or design of any geotechnical structure (retaining wall, unsupported slope, foundation) 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 one equation:

$$\text{Resistance (Capacity)} > \text{Loads (Demand)} \qquad \textbf{(1)}$$

The extent to which resistance of a structure exceeds the loads applied to it is "safety" and this can be incorporated to the required or desired level using the traditional Allowable Stress Design (ASD)/Working Stress Design (WSD) approach or the more modern Load-and-Resistance Factor (LRFD)/Ultimate Strength Design (USD) approach.

Historically, civil engineers have been educated to satisfy Eq. 1 in the majority of cases by increasing the left-hand or "resistance" side of the equation. The loads, generally dictated by nature either directly or indirectly, are generally accepted as is and structural 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.

While this traditional approach has and continues to serve the profession well, it is important to note that it is not the only way to satisfy Eq. 1. Specifically, the right-hand or "load" side of the equation can be reduced. Alternatively, there can also be some combination of load reduction and resistance increase. Regardless of the specifics, it is worth noting that the concept of load reduction works particularly well for geotechnical structures because in many problem categories, especially those involving earth-retaining structures and unsupported slopes, a significant portion of the design loads comes from the mass of the soil itself under gravity or seismic acceleration. Therefore, a potential alternative for earth-retaining structure development is to develop technologies where loads are reduced as part of an overall strategy to satisfy Eq. 1.

LOAD-REDUCTION ALTERNATIVES

Overview

Engineers seeking to reduce loads on earth-retaining structures, whether as part of new construction or the rehabilitation/upgrading of an existing structure, have two broad alternatives available to them:

- use a "lightweight" ("low density" or "low unit weight" is arguably a more-correct term) material for some portion of the fill/backfill behind the structure, and
- use a compressible inclusion to induce or allow controlled yielding within a normal soil fill/backfill.

The former alternative is intuitive and is not the focus of this paper although some comments are provided in the following section. The latter alternative is the more technically novel one and is the primary focus of this paper.

Lightweight Fill Materials

Although not the focus of this paper, it is worth noting that there is a wide range of different manufactured and waste materials with solid and particulate textures that have been used for this purpose. Perhaps the single most important thing to keep in mind is that "lightweight" is a relative term and simply means a material has a density or unit weight less than that of normal earth materials. Thus there can be, and is, a rather large variation of "lightness" within the overall category of lightweight fill. Consequently, there can be a corresponding wide range of load reduction behind a earth-retaining structure. However, it is worth noting that by using expanded polystyrene (EPS) geofoam, which is the lightest of the lightweight material with a density only about 1% that of normal soil, the horizontal forces acting on an earth-retaining structure, at least from gravity and seismic loads, can be reduced to very small magnitudes.

The negatives with using lightweight fills in earth-retaining structure applications is that relatively large volumes of material are required. With few exceptions (the major one being subsidized waste materials), lightweight fill materials are generally much more expensive than soil on a volume basis. In addition, to achieve significant benefits lightweight material must be placed to a relatively large distance behind the earth-retaining structure. This can pose constructability issues for both new and existing structures.

Further discussion of lightweight fill materials is beyond the scope of this paper. A reasonably comprehensive and up-to-date discussion of them, but with an intentional bias toward transportation applications, can be found in *Matériaux* (1997). A discussion of the use of EPS geofoam, which is currently the lightweight fill material of choice in many cases, in a wider range of applications can be found in Horvath (1995).

Controlled Yielding

Controlled yielding is a term used nowadays to describe the generic use of a relatively soft material (referred to herein as a compressible inclusion) between the ground and a relatively rigid and/or non-yielding (non-displacing) structure that is placed adjacent to the ground. The function of the compressible inclusion is to allow the ground to displace, at least to some extent, adjacent to the structure in a situation where its displacement would otherwise be restricted or even prevented entirely due to the constraints imposed on it by the structure. The benefit of doing this a reduction in earth forces acting on the structure. This can translate into reduced costs for new construction or improved performance (an increase in "safety" in the context of Eq. 1) for existing structures.

There are numerous potential applications of the controlled-yielding concept. A broad overview can be found in Horvath (1995) with a more-focused introduction in Horvath (1996, reproduced in Horvath 1998a). A detailed bibliography of publications related to controlled yielding as of the end of 2000 can be found in Horvath (2001). An assessment of all the compressible-inclusion applications identified to date indicates that those related to earth-retaining structures have the greatest potential for diverse and widespread use. As such, this is the focus of this paper.

It is of interest and relevance to note that although the terms controlled yielding and compressible inclusion are relatively new, the overall concept is not. In fact, the published record clearly indicates that engineers recognized and used this concept at least as far back as the early part of the 20th century when bales of hay and straw were placed above underground conduits (pipes) to induce vertical arching (a phenomenon that is one manifestation of controlled yielding) and thereby reduce vertical stresses acting on the conduits (Spangler and Handy 1982). This usage predates the formal development of modern soil mechanics and publication of Terzaghi's theoretical treatment of the subject of vertical arching (Terzaghi 1943).

However, although it is clear that the concept of controlled yielding using a compressible inclusion is relatively old, it is equally clear it has been significantly underexploited to date. It appears that one of the main reasons for this is the lack of a compressible-inclusion material that is both predictable in its behavior and durable in the ground, something that organic materials such as hay, straw or cardboard (a product used in more-modern times, including behind earth-retaining structures) are not. This situation has now been resolved with the global emergence and recognition of geofoams during the 1990s. Certain geofoam materials and products have proven to be remarkably well suited for use as compressible inclusions. Consequently, there are no longer any barriers to using controlled yielding as a design tool, especially with earth-retaining structures.

GEOFOAM BASICS

Introduction

The rapid spread of knowledge about geofoams that occurred during the 1990s and which continues to the present has, unfortunately, resulted in the spread of some incorrect information about them. Consequently, it is useful to review some basic facts concerning geofoam materials, functions and products.

Materials

Geofoam is now recognized as the generic name for a type or category of *cellular geosynthetic* along with *geocombs* (Horvath 2003). Geofoams include any type of close-cell foam used in a geotechnical application and include a wide variety of different types and formulations of polymeric (plastic) foams as well as foams made from portland-cement concrete (PCC) and glass. A discussion of the complete range of geofoam materials can be found in Horvath (1995).

Geofoams have been used since at least the 1960s although they were not generically referred to as such until the 1990s. Consequently, there has been sufficient time to try and evaluate different materials in geofoam applications. As discussed in the following section, geofoams are possibly the most diverse category of geosynthetics in terms of the number of different geosynthetic functions (roles) they can provide. However, experience to date clearly indicates that the geofoam material of choice for most functions (including compressible inclusions) is a polymeric material called *expanded polystyrene* (EPS). EPS is the familiar white-colored foam (although it can be colored otherwise for marketing purposes) that is seen in many consumer applications such as cushion packaging, and beverage and food containers. There are numerous reasons for its primacy as a geofoam material (so much so that some people mistakenly think of EPS as the only geofoam material). Chief among them are that its behavioral properties are well matched to civil engineering needs and that it is locally manufactured and thus readily available in most every country in the world.

The material properties of EPS that are of interest to civil engineers are discussed in detail in Horvath (1995). The key properties that are relevant to its use as a compressible inclusion are:

- It has a very low density (in the range of 10 to 30 kg/m^3 (a unit weight of 0.6 to 1.9 lb/ft^3)). In fact it is the lightest lightweight material known, so is very easy to handle.
- Its compressibility (modulus), which correlates to its density with sufficient predictability, can be made to be relatively low compared to other civil engineering materials. This is beneficial in compressible-inclusion applications.
- Its compressibility can be reduced even further by an additional manufacturing step called *elasticization*. The resulting material is referred to as *resilient* or *elasticized* EPS.
- It is both durable and environmentally friendly in a typical geotechnical environment.

Functions

It is now appreciated that the key to using any geosynthetic in engineered construction is to identify the function(s) that the geosynthetic product or combination of products must provide. Only then can the geosynthetic be rationally designed.

Using geofoams is no exception to this guideline. A detailed discussion of all the potential functions of geofoam is beyond the scope of this paper but can be found in numerous other sources, e.g. Horvath (1995, 2003). Of relevance to this paper is the fact that:

- With one exception (the function of *fluid transmission*), geofoams as a group provide functions that no other traditional "planar" geosynthetics (geogrid, geomembrane, geotextile) can provide. This provides engineers with many additional design tools not previously available with planar geosynthetics.
- In many if not most applications where controlled yielding behind an earth-retaining structure is the primary reason for using a geofoam compressible inclusion, one or more additional geofoam functions can realistically be beneficial. This includes providing drainage of both ground water and ground-borne bases, thermal insulation, and noise and vibration attenuation.
- Of all the geofoam materials currently known, only EPS or materials related to EPS can realistically be used to provide every geofoam function.

In summary, experience indicates that by recognizing the multifunctionality of EPS geofoam it is often possible to use one geocomposite product to cost effectively serve not only as a compressible inclusion for controlled yielding but

Products

As will be seen in the following section, geofoam compressible inclusions used adjacent to earth retaining structures are typically placed as relatively thin (of the order of 100 to 150 mm (4 to 6 in) thick), continuous layers. Thus far less material is required compared to a typical lightweight-fill application. Experience to date indicates that for such applications it is typically most economical to manufacture the geofoam product in panels that are typically of the order of one metre (40 in) square and of the full thickness desired for the application. Such panels can then be easily handled and glued to one face of the earth-retaining structure.

The exact composition of a panel depends on the functions that the design engineer desires. For almost all applications involving earth-retaining structures, the sole or at least primary component would be resilient EPS such as *TerraFlex*® that is manufactured by GeoTech Systems Corporation in the U.S.A. In most applications, drainage is also a desired function and this is typically achieved by factory-laminating a drainage geocomposite to one face of the panel. Such geocomposites typically consist of a high-permeability core that provides the fluid transmission covered by a non-woven geotextile to provide separation and filtration. Where available, the most cost-effective drainage geocomposite to use in compressible-inclusion applications is one with a *glued porous polystyrene* (a geofoam material that is related to EPS) core such as the *GeoTech Insulated Drainage Panel*™. This is because this particular type of drainage geocomposite adds to the overall compressibility that is highly desirable in a controlled-yielding applications. In the U.S.A. this combination of resilient EPS and geofoam-based drainage geocomposite, which is called the *Geoinclusion*®, has proven to be the compressible-inclusion product of choice in most earth-retaining structure applications.

APPLICATIONS TO EARTH-RETAINING STRUCTURES

Introduction

To date, there are two broad categories of controlled-yielding application that have been identified for use with earth-retaining structures:

- the *Reduced-Earth-Pressure Concept* and
- the *Zero-Earth-Pressure Concept.*

Each of these has been studied to varying extents since the mid 1980s. Most of this study has involved either small-scale model testing under 1*g* conditions (no centrifuge testing is known to have been performed) or numerical analyses using a finite-element solution of a continuum. There has been relatively little published data for full-scale testing or case-history observations to date.

Collectively, these studies have been both necessary and useful for exploring the basic behavior of these 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 numerical analyses must be developed. Therefore, this paper will focus on the state of development of such simple models intended for use in routine practice as opposed to fundamental research.

Reduced-Earth-Pressure (REP) Concept

Overview

This category of application is illustrated in Fig. 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 not intended to be limited to a gravity retaining wall. It can be any type of rigid retaining wall, bridge abutment, below-grade (basement) wall of a building, navigational lock, etc.

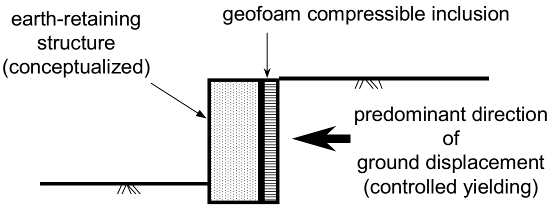

Fig. 1. Conceptual Illustration of Components of the Reduced-Earth-Pressure (REP) Concept

In most cases, the primary design variable is the stiffness of the compressible inclusion which is defined as the Young's modulus of the geofoam material divided by its thickness. Recently (Horvath 2000), it was found useful to establish a new dimensionless parameter, λ, called the *normalized compressible inclusion stiffness*, for the purpose of comparing stiffnesses of compressible inclusions. This parameter is defined as follows:

$$\lambda = \frac{E_{ci} \cdot H}{t_{ci} \cdot p_{atm}} \tag{2}$$

where E_{ci} is the Young's modulus of the compressible inclusion material, H is the geotechnical height of the earth-retaining structure, t_{ci} is the thickness of the compressible inclusion in the direction parallel to the predominant direction of ground displacement as shown in Fig. 1, and p_{atm} is the atmospheric pressure constant. For reference purposes, the limiting values of λ are zero for the "perfectly compressible" case of unrestricted displacement (i.e. a perfectly-soft compressible inclusion) and infinity for the "perfectly rigid" case of no displacement. Quantitatively, the smaller the value of λ the more compressible the inclusion is.

Note that some thought always needs to be given to the appropriate value of E_{ci} to use in Eq. 2. This is because the geofoam material or materials will almost certainly be polymeric and such materials are susceptible to creep over most of their load range. Thus a modulus should be chose that is consistent with the time frame over which the ground will develop its load.

Regardless of the specific REP application, the basic manner in which the compressible inclusion works and is designed is illustrated in Fig. 2. The ground will have some force-displacement relationship that is dictated by the particular soil and application. In general, the greater the ground displacement in extension the smaller the force the ground will exert on the earth retaining structure. As will be seen subsequently, the ground force may or may not go to zero in the limit. On the other hand, the geofoam compressible inclusion, over which the design engineer has complete control, has a reciprocal behavior in that the more it displaces in compression the greater the force that is required. The design process is to match the stiffnesses of the ground and compressible inclusion to produce a reduced force on the earth-retaining structure. As will be seen, depending on the specific application there may or may not be a theoretical unique solution to the problem, i.e. unique required thickness of geofoam.

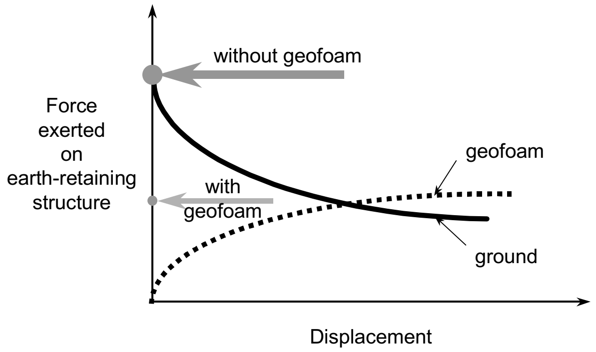

Fig. 2. Conceptual Illustration of Physical Behavior of the Reduced-Earth-Pressure (REP) Concept

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

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 use of 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 active earth pressure state develops in situations where design for the at-rest (or larger) lateral earth pressure state would normally be appropriate. Thus in Fig. 2 the force exerted by the ground would plateau at some non-zero magnitude after a certain amount of lateral displacement, Δ_a, of the soil mass (historically this has usually been expressed as the dimensionless ratio Δ_a/H). Because the earth force reaches and remains at this limiting minimum value, this is one of those applications where there is a unique solution in terms of required thickness of the geofoam product in that a thicker product would provide no benefit.

For simplicity, it is generally assumed that the distribution of lateral earth pressures achieved using a compressible inclusion in this manner will follow the traditional triangle assumed for both the Coulomb and Rankine classical solutions for the active earth pressure state. However, a wide variety of numerical as well as observed results consistently indicate a curved distribution as shown in Fig. 3 which was taken from Horvath (2000). In retrospect, such a result should not be surprising as the use of the REP concept behind an earth-retaining structure is, in essence, inducing horizontal arching within the soil. Such curved distributions of lateral earth pressures are completely consistent with theoretical results expected based on various derivations of arching theory (Handy 1985, Harrop-Williams 1989). The limiting lateral earth pressure conditions are also shown in this figure using the normalized compressible inclusion stiffness (λ) parameter introduced earlier.

In developing a simplified design methodology for this basic application of the REP concept, the writer has taken the position that design should be based on the active resultant force, not pressures. How a designer chooses to distribute this force along the back of an earth-retaining structure is a matter of choice. As discussed in detail in Appendix A of Horvath (2000), the development of a simplified solution for this basic application of the REP concept has gone through several evolutionary changes since it was first proposed by Partos and Kazaniwsky (1987). The current version (2.0) developed by the writer is

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

where K_a is the active earth pressure coefficient obtained using either Coulomb or "exact" theory, δ is the friction angle between the retained soil and the geofoam compressible inclusion material, and γ_t is the total unit weight of the retained soil.

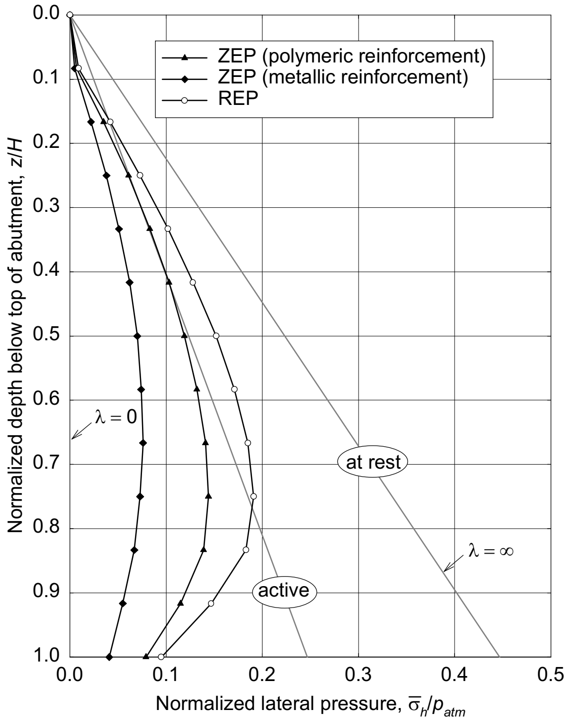

Fig 3. Comparison of Lateral Earth Pressure Distributions

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 that are due to the structure itself, not as a result of the structure reacting to earth loads. This is usually the result of the earth-retaining structure's being subjected to thermal loads (an observed phenomenon for wastewater treatment facilities (England 1994) and navigational locks for example) or being structurally connected to some superstructure that moves as in the case of integral-abutment bridges (Horvath 2000).

The importance of this phenomenon overall is that it can lead to relatively large lateral earth pressures, i.e. well in excess of the at-rest state and tending toward the passive, which can and has led to structural failure of the earth-retaining structure. It is generally much more economical to use a compressible inclusion to accommodate or "cushion" structure movement within a minimized increase in lateral earth pressures than to design or reinforce it to withstand these pressures. A generic, simplified design methodology for geofoam compressible inclusions used in these situations has not been developed to date and may prove difficult given the diversity and complexity of these applications. However, it may prove possible to develop a simplified design procedure for each problem category, e.g. integral-abutment bridges.

Accommodating Volume Change of Earth Materials

An application of considerable interest worldwide involves situations where the ground retained by an earth-retaining structure is susceptible to volume changes simply due to environmental conditions, most commonly changes in water content. This encompasses the well known problem of*expansive* or *swelling* soils. Normally such soils would not be used as backfill/fill behind an earth-retaining structure or, conversely, an earth-retaining structure would not be built where such soils are the only ones available for use. This is broadly for the same reason as described in the preceding section for structure-induced movement. However, in the case of expansive soils the lateral earth pressures generated can be extremely large.

Geofoam compressible inclusions offer the potential for a technically-acceptable and cost-effective alternative that would allow use of expansive soils as backfill/fill behind earth-retaining structures. There has been some analytical work to date that supports this (Aytekin 1997). In addition, the use of geofoam compressible inclusions beneath foundation slabs to relieve vertical stresses from expansive soil is a well-proven application which also supports the validity of the basic concept.

One thing to keep in mind with regard to using geofoam compressible inclusions to reduce lateral earth pressures from expansive soils is that, with reference to Fig. 2, the ground force will actually go to zero at some displacement. This means that there is never a unique thickness of geofoam to use in such applications. Rather, there is a range of thicknesses. In practice, a value could be selected that provides the best overall economy of both the earth-retaining structure and geofoam material costs.

Zero-Earth-Pressure (ZEP) Concept

Overview

This application concept evolved from the REP concept and is illustrated in Fig. 4. Note that the earth-retaining structure shown is again conceptual and that the placement of the geofoam compressible inclusion and the primary direction of ground displacement are both exactly the same as in the REP case shown in Fig. 1. The unique 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 self-stable mechanically stabilized earth wall (MSEW) is constructed behind the primary earth-retaining structure.

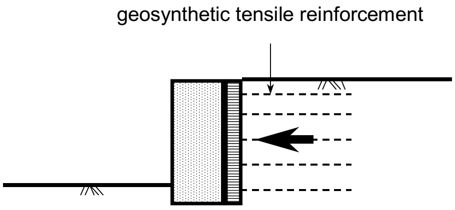

Fig. 4. Conceptual Illustration of Components of the Zero-Earth-Pressure (ZEP) Concept

With regard to designing the stiffness of the compressible inclusion for ZEP applications, the same basic procedure as discussed previously for the REP concept and illustrated qualitatively in Fig. 2 applies here. A significant difference is that in all cases and for all types of soil the ground force in Fig. 2 will eventually become zero at some displacement. This behavior is what gave the ZEP concept its name.

Composite Shear-Strength and Tensile-Reinforcement Mobilization

The potential of the ZEP concept has barely been exploited in practice to date. However, it is likely that in most cases a designer would use this concept simply to simultaneously mobilize the inherent shear strength of the retained soil and allow the tensile reinforcement to strain tensilely so as to reduce the lateral earth forces to smaller magnitudes than could be achieved using the REP concept alone (it turns out that settlement of the surface of the retained soil is also reduced, an additional benefit). This is illustrated in Fig. 3 for a problem considered in Horvath (2000). Note that this figure does not intend to imply the superiority of one type of geosynthetic tensile reinforcement over another. It merely shows that, for the same magnitude of compressible inclusion stiffness, λ, the lateral earth pressures are sensitive to the stiffness of the tensile reinforcement used, if any.

It should be noted that in any and all ZEP-concept applications there is never is a unique "correct" thickness of geofoam to use. Rather there is a range of thicknesses and one should, ideally, be chosen based on a rational assessment of minimizing the total cost of the primary earth-retaining structure, and geofoam and reinforcement materials.

With regard to developing simplified design methods, work with the ZEP concept is much less developed compared to the REP concept. This is because of the added complexity of having to define the horizontal stiffness of the reinforced retained soil mass. An initial postulation of a simplified design procedure was made in Horvath (1997, reproduced in 1998b) and was substantially revised (Version 2.0) in Section 3.3.3.10 of Horvath (2000). It is somewhat too lengthy to reproduce here but is easily solved by manual calculation. Limited comparison of results obtained using this method with more-rigorous numerical results show the simplified method to be quite conservative. Clearly, this is an area requiring further improvement and it appears the top priority is to allow better estimation the horizontal stiffness of the reinforced retained soil mass.

Accommodating Structure-Induced Movement

This application is identical to that discussed previously under the REP concept. The primary benefit of using the ZEP as opposed to REP concept with a moving earth-retaining structure is not so much the reduction of lateral earth pressure when the structure moves away from the retained soil (there is, theoretically, no difference when the structure moves into the soil) but the fact that the reinforced soil mass that is part of the ZEP concept significantly restricts soil settlement adjacent to the earth-retaining structure. This consideration is important when dealing with structures such as integral-abutment bridges in order to prevent or at least limit development of the problematic "bump at the end of the bridge" (Horvath 2000).

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DISCLAIMER

Reference in this paper to proprietary, tradenamed products is solely for informational purposes and does not constitute an endorsement of said products, etc. by the writer, CGT or Manhattan College.

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