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**GEOFOAM COMPRESSIBLE INCLUSIONS:
THE NEW FRONTIER IN EARTH RETAINING STRUCTURES**

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ABSTRACT: A *compressible inclusion* in the broadest sense of the term is any relatively compressible material that is intentionally placed between a rigid and/or non-yielding structure and the ground that would otherwise be in direct contact with it. This allows the ground to yield or displace. The primary benefit is reduced earth pressures acting on the structure which can either reduce the cost of a new structure or enhance the performance of an existing one.

This paper outlines the basic ways in which modern, engineered compressible inclusions are used with earth-retaining structures to produce *controlled yielding* and predictable results. Typical materials used, which nowadays are usually some type of geofoam geosynthetic, and specific transportation-related applications are also described. Because of the diversity of applications and the fact that there are usually multiple benefits to using them, the use of geofoam compressible inclusions has the potential to significantly and permanently impact they way in which earth-retaining structures are designed, constructed, maintained, rehabilitated, and upgraded.

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:

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

Historically, civil engineers have satisfied Eq. 1 by increasing the resistance side of the equation. The loads, generally dictated by nature either directly or indirectly, are accepted as is and material is added to the structure so that Eq. 1 is satisfied from

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both a stiffness (*serviceability limit state*, SLS) and strength (*ultimate limit state*, ULS) perspective.

There are, however, other ways to satisfy Eq. 1. The 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 problem categories, especially those involving earth-retaining structures, a significant portion of the design loads come from the mass of the soil itself under gravity or seismic acceleration.

LOAD-REDUCTION ALTERNATIVES

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* (controlled displacement) within a normal soil fill/backfill.

A discussion of lightweight-fill materials is not part of this paper as sufficient publications on the subject already exist. The use of lightweight-fill materials represents a mature geotechnology that has been used worldwide for more than 30 years. A fairly complete presentation of the various available materials, with an intentional emphasis on transportation applications, can be found in PIARC (1997). A comprehensive discussion of the use of block-molded expanded polystyrene (EPS-block) geof foam, which is currently the lightweight-fill material of choice in most cases, can be found in Horvath (1995) and Stark et al. (2002). This paper focuses on the use of compressible inclusions to induce or allow controlled yielding as this is a lesser-known geotechnology but one that offers great potential.

Controlled yielding is the generic use of a relatively thin/compressible layer of 'engineered' material (the compressible inclusion) between the ground and a rigid and/or non-yielding (non-displacing) structure that would normally be in direct contact with the ground. The primary function of the compressible inclusion is to sacrificially compress and allow the ground to displace adjacent to the 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 for existing structures.

There are numerous potential applications of soil yielding in general 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 and culverts) to induce vertical arching and reduce the vertical forces acting on conduits. However, what makes controlled yielding different is that geosynthetic materials that are both durable and predictable in their behavior (something which organic materials such as hay, straw or cardboard are definitely not) are used for the compressible inclusion.

The use of such materials is what has turned an uncontrollable, unpredictable phenomenon into one that is consistent with modern geotechnical engineering.

In particular, it was the evolution of block-molded expanded polystyrene (EPS-block) geofoam during the latter decades of the 20th century that provided the basic durable, predictable material which made greater use of the controlled-yielding concept practicable. A complete discussion 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). A detailed bibliography of publications related to controlled yielding can be found in Horvath (2001).

APPLICATIONS TO EARTH-RETAINING STRUCTURES

Introduction

An assessment of compressible-inclusion applications identified to date indicates that those related to earth-retaining structures, especially in transportation applications, have the greatest potential for use. 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 has been studied to varying extents since the mid 1980s. Most of this study has involved either small-scale model testing under 1g 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 development of 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 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 not intended to be limited to a gravity retaining wall. It can be any type of relatively rigid structure such as a retaining wall, bridge abutment, below-grade (basement) wall of a building, or navigational lock.

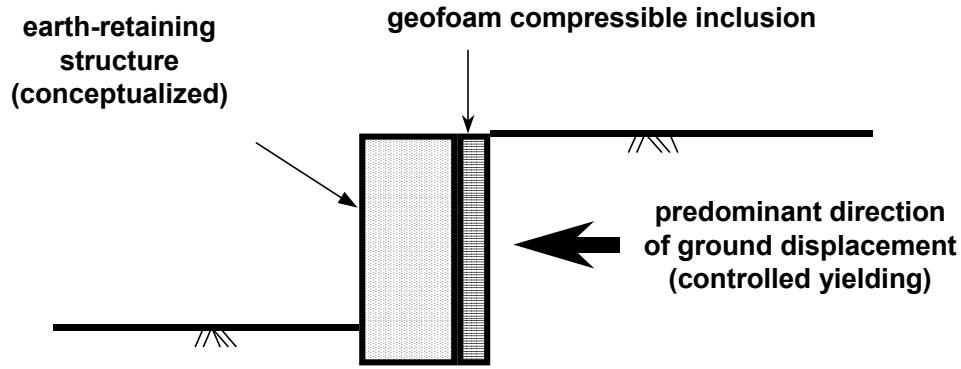


FIG. 1. Conceptual Illustration of the Reduced-Earth-Pressure (REP) Concept

In most applications, the primary design variable is the compressive stiffness of the compressible inclusion which is defined as the Young's modulus of the compressible-inclusion material divided by its thickness. Recently, it was found 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 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; and p_{atm} is atmospheric pressure. 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 functions and is designed is illustrated in Figure 2. The ground has some force-displacement relationship that is dictated by the particular soil or rock 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. On the other hand, the geofoam compressible inclusion has a reciprocal behavior in that the more it displaces in compression the greater the force that is required. Both the ground and compressible inclusion can be visualized as springs (note, however, that this does not imply that they behave as a Winkler subgrade) and the design process is to match the stiffnesses of the ground and compressible-inclusion 'springs' to produce a reduced force on the earth-retaining structure. Depending on the specific application, there may or may not be a unique solution, i.e. unique required thickness of geofoam.

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

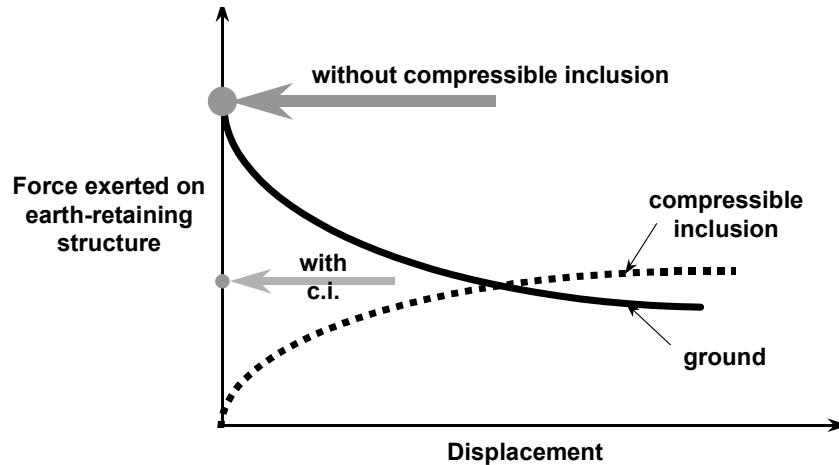


FIG. 2. Qualitative Behavior of the REP Concept

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 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 Figure 2 the force exerted by the ground (soil) plateaus at a 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 an application where there is a unique solution in terms of required thickness of the compressible inclusion in that a thicker one would provide no theoretical 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 triangular distribution assumed for the active-earth-pressure state. However, numerical analyses as well as observed results from both model tests and actual structures consistently indicate a curved, roughly parabolic distribution as shown in Figure 3. Such a result is not 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 for arching theory (Handy 1985; Harrop-Williams 1989).

In developing a simplified design methodology for this application of the REP concept, the position has been taken that the active resultant force, not pressures, be used as the primary parameter. How this calculated force is distributed as a stress along the back of an earth-retaining structure is a matter of choice. As discussed in detail in Horvath (2000), the development of a simplified solution for the REP concept has gone through several evolutionary changes since it was first proposed by Partos and Kazaniwsky (1987). The current version presented in Horvath (2000) is

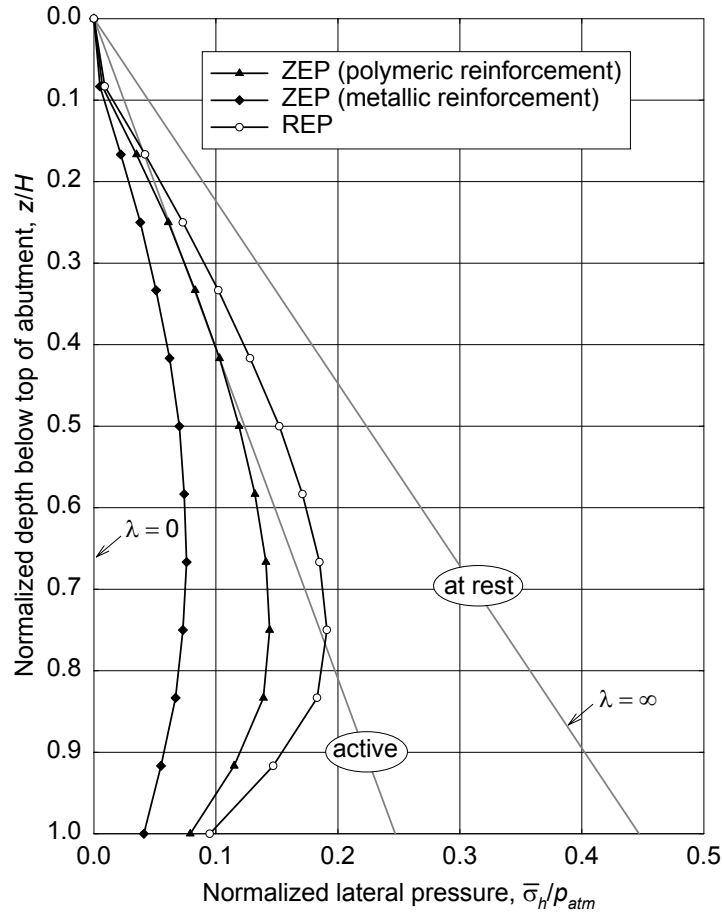


Fig. 3. Comparison of Lateral Earth Pressure Distributions (Horvath 2000)

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

where K_a is the active earth pressure coefficient obtained using either Coulomb or some 'exact' (e.g. log-spiral) theory (but not Rankine which is theoretically incorrect to use here); δ is the friction angle between the retained soil and the geofabric compressible-inclusion material; and γ_t is the total unit weight of the retained soil.

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 (wastewater treatment facilities (England 1994) and navigational locks for example) or being physically connected to

some structure that moves (integral-abutment bridges for example (Horvath 2000; Horvath 2004)).

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, which can lead to structural failure of the earth-retaining structure. 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 generic, simplified design methodology for geofam compressible inclusions used in these situations has not yet been developed and may prove challenging 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 related to economics as described in the preceding section for structure-induced movement. However, in the case of expansive soils the earth pressures generated can be extremely large and exceed what can be designed for economically.

Geofam 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 preliminary analytical work that supports this (Aytekin 1997). In addition, the extensive use of geofam compressible inclusions beneath foundation slabs to relieve vertical stresses from expansive soil is a well-proven application that also supports the validity of the basic concept.

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

Zero-Earth-Pressure (ZEP) Concept

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 feature of the ZEP concept compared to the previously discussed REP concept is the embedment of

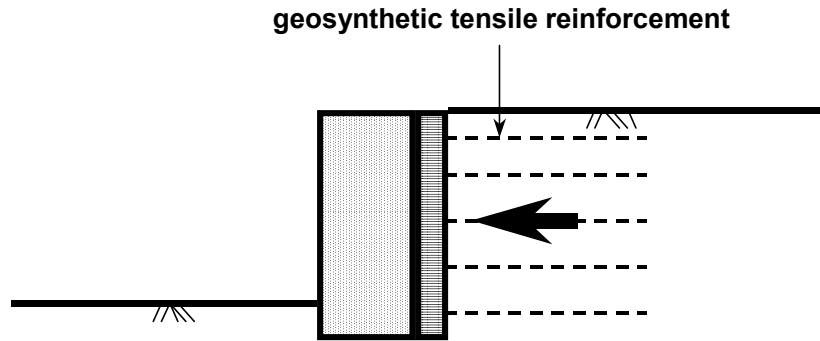


FIG. 4. Conceptual Illustration of the Zero-Earth-Pressure (ZEP) Concept

multiple layers of geosynthetic tensile reinforcement (metallic or polymeric) within the retained soil. In essence, a more-or-less self-stable mechanically stabilized earth wall (MSEW) is constructed behind the primary earth-retaining structure.

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 Figure 2 applies. A significant difference is that in all cases and for all types of soil the ground force in Figure 2 will eventually become zero at some displacement, at least in theory. This is because at some magnitude of horizontal displacement the geosynthetic tensile reinforcement becomes fully activated. This behavior is what gave the ZEP concept its name. However, in practice there will be some small lateral earth pressure on the earth-retaining structure simply because a zero-stiffness compressible-inclusion material does not physically exist.

Composite Shear-Strength and Tensile-Reinforcement Mobilization

The potential of the ZEP concept has barely been explored or exploited to date. However, it is likely that in most cases this concept would not be used to maximize reduction of lateral earth forces but to reduce them to some magnitude smaller than what can be achieved using the REP concept alone. This reduction would accrue from both mobilizing the inherent shear strength of the soil as well as some portion of the tensile capacity of the geosynthetic reinforcement. This is illustrated in Figure 3 for the same problem analyzed using the REP concept. Note 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.

It should be noted that in any and all ZEP-concept applications there is never a unique 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 'spring' stiffness of the reinforced retained-soil mass. An initial postulation of a simplified design procedure was made in Horvath (1997; republished in Horvath 1998b) and was substantially revised in Horvath (2000). It is 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 current simplified method to be conservative. Clearly, this is an area requiring further improvement and it appears the top priority is 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 displacing earth-retaining structure such as an integral-abutment bridge 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; Horvath 2004).

ADDITIONAL GEOSYNTHETIC FUNCTIONS AND BENEFITS

This paper has intentionally focused on the primary geosynthetic function of geofoam compressible inclusions to reduce lateral earth pressures. It is important to note that additional functions such as drainage and thermal insulation are or can be provided by the geofoam product which enhances the technical benefits and cost effectiveness of using such products.

MATERIALS DEVELOPMENT

As noted previously, EPS is the basic geofoam material of choice for virtually all compressible-inclusion applications nowadays. However, there has been a substantial amount of materials research during the 1990s to develop geofoam products especially for compressible-inclusion applications. For example, depending on the particular application it is often cost effective to use EPS that has been modified during manufacture to be more resilient ('elasticized') as well as to use various high-porosity EPS-related materials when drainage is also desired.

CONCLUSIONS

The use of compressible inclusions in transportation-related applications to reduce lateral earth pressures on a wide variety of earth-retaining structures has enormous potential. There are few such structures that could not benefit in terms of performance and cost from using such materials. In most applications, the required thickness of the

compressible inclusion is quite modest, typically less than one foot (300 mm). Considering that a drainage layer can easily be incorporated within this thickness (most earth-retaining structures in transportation applications require positive drainage for ground water 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.

REFERENCES

- Aytekin, M. (1997). "Numerical modeling of EPS geofam used with swelling soil." *Geotextiles and Geomembranes*, Elsevier Sci. Ltd., U.K., 15 (1-3), 133-146.
- England, G. L. (1994). "The performance and behaviour of biological filter walls as affected by cyclic temperature changes." *Serviceability of Earth Retaining Structures*, R. J. Finno (ed.), ASCE, 57-76.
- Handy, R. L. (1985). "The arch in soil arching." *J. Geotech. Engr. Div.*, ASCE, 111 (3), 302-318.
- Harrop-Williams, K. O. (1989). "Geostatic wall pressures." *J. Geotech. Engr. Div.*, ASCE, 115 (9), 1321-1325.
- Horvath, J. S. (1995). *Geofoam geosynthetic*, Horvath Engr., P.C., Scarsdale, NY.
- Horvath, J. S. (1996). "The compressible inclusion function of EPS geofam: an overview." *Proc. of the Intl. Sym. on EPS Construction Method (EPS Tokyo '96)*, EPS Development Organization, Japan, 71-81.
- Horvath, J. S. (1997). "The compressible inclusion function of EPS geofam." *Geotextiles and Geomembranes*, Elsevier Sci. Ltd., U.K., 15 (1-3), 77-120.
- Horvath, J. S. (1998a). "The compressible inclusion function of EPS geofam: an overview of concepts, applications, and products." *Res. Rpt. No. CE/GE-98-1*, Manhattan Coll., Sch. of Engr., Civil Engr. Dept., Bronx, NY.
- Horvath, J. S. (1998b). "The compressible-inclusion function of EPS geofam: analysis and design methodologies." *Res. Rpt. No. CE/GE-98-2*, Manhattan Coll., Sch. of Engr., Civil Engr. Dept., Bronx, NY.
- Horvath, J. S. (2000). "Integral-abutment bridges: problems and innovative solutions using EPS geofam and other geosynthetics." *Res. Rpt. No. CE/GE-00-2*, Manhattan Coll., Sch. of Engr., Civil Engr. Dept., Bronx, NY.
- Horvath, J. S. (2001). "Geomaterials research project - geofam and geocomb geosynthetics: a bibliography through the second millennium A.D." *Res. Rpt. No. CGT-2001-1*, Manhattan Coll., Sch. of Engr., Ctr. for Geotechnology, Bronx, NY.
- Horvath, J. S. (2004). "Integral-abutment bridges: a complex soil-structure interaction challenge." *Proc. Geo-Trans 2004*, ASCE.
- Partos, A. M. and Kazaniwsky, P. M. (1987). "Geoboard reduces lateral earth pressures." *Proc. Geosynthetics '87*, IFAI, St. Paul, MN, 628-639.
- PIARC Tech. Comm. C12 on Earthworks, Drainage, Subgrade. (1997). "Matériaux legers our remblai/lightweight filling materials." *Document No. 12.02.B*, PIARC - World Road Association, France.
- Stark, T. D., Arellano, D., Horvath, J. S. and Leshchinsky, D. (2002). *Guidelines for geofam applications in embankment projects*, Final Rpt. - Natl. Coop. Hwy. Res. Prog. Proj. No. 24-11.