Cost Savings by Using Geosynthetics in the Construction of Civil Works Projects

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ABSTRACT: This paper provides an evaluation of cost savings, which can be directly attributed to the use of geosynthetics in the construction of civil works features such as roads, embankments, retaining structures, erosions control features, drainage systems, reservoirs, and waste containment systems. Four types of cost savings are identified including: 1) reduction of the quantity or need for select soil materials; 2) easier and/or accelerated construction; 3) improved long-term performance; and, 4) improved sustainability. In many applications, combinations of cost benefits are identified, and, in most of these cases, the value far exceeds the as-installed cost of the geosynthetic. A review of each of these potential cost benefits is provided for routine applications. Project information from bid price records and project examples, where specific cost savings results have been documented, are used to support the identified cost benefits. Methods of estimating improved long-term performance cost benefits are discussed and example calculations from one the methods are included. Future potential cost benefits are also recognized from new geosynthetic products and applications.

Keywords: geosynthetics, cost-benefit, life cycle cost, construction, performance, sustainability

1 INTRODUCTION

Geosynthetics have been used in civil works construction for over 50 years, offering the opportunity to evaluate the long-term cost benefits of using geosynthetics in these applications. Unfortunately, this is not the case as most projects using geosynthetics have not been well documented, especially over the life of the project, and in many cases, documentation does not even include the initial cost. Geosynthetics are often used as component(s) of a constructed system (e.g., pavement system). Project costs often do not break out the individual components (i.e., the geosynthetic or its installation). Even if those costs are available, actual costs are often mixed in with other project costs, and, in some cases, inflated to provide a more lucrative return to the contractor (i.e., increasing the price almost to the higher alternative cost). Geosynthetics are often used to improve the system or may make it more efficient, but even information for evaluating the performance of the system is often not available (e.g., control sections for comparison are often missing).

In the US and Europe, industry and professional organizations have attempted to acquire cost and performance on a broad basis with little success. Fortunately, individual efforts (e.g., by design engineers, researchers, and owner's or manufacturer's representatives), have succeeded in monitoring some projects and provide support for the findings in this paper. Within government agencies, there have been a number of projects where cost and/or performance of several alternatives are compared to using geosynthetics. Unfortunately many of these studies were just monitored during initial construction or, in some cases, only over the first few years. While that initial work provides valuable information in developing short term cost comparisons, it does not represent the true value of the geosynthetic since long term performance is not evaluated. The author has made a number of attempts to identify these projects and encourage long-term performance evaluation, but has not had significant success. Hopefully this paper will inspire others to do so. The projects that have been identified and re-evaluated provide valuable information to support the conclusions in the paper.

This paper provides a summary of the cost benefits gathered from the projects that have been documented, in terms of either short-term cost and/or long-term performance. The available information, and thus the paper, is somewhat dominated by geosynthetics in roadway applications, as a majority of geosynthetics are used in roadways. Also, the design performance period for roadway applications is relatively short (typically on the order of 20 to 30 years and even shorter for pavement overlay applications) and, in many cases, the use of geosynthetics has spanned several life cycles; consequently long-term performance has also been more extensively documented. Other applications such as walls and waste containment systems typically have performance periods of over 100 years and long-term performance information is only available for the early years of the project life. In some cases, where only limited data is available, a group of similar projects was evaluated to obtain an idea of the cost benefits of using geosynthetics for that application, either by the author or others as referenced in the paper.

The cost benefits of using geosynthetics may be immediate, long-term or both. In the review of the projects for this paper, four cost savings benefits were identified including:

1) immediate savings through substitution or reduction of select soil materials,
2) immediate savings through ease of installation and/or increased speed of construction,
3) life cycle cost savings through improved performance as measured by increased longevity or reduction of maintenance, and
4) improved sustainability in terms of conserving natural environments as compared to alternate designs.

The following sections provide a description of each of these types of cost savings and a review of the potential cost benefit for routine applications. Where available, project information from bid price records and project examples where specific cost savings results have been documented are used to support the identified cost benefits (e.g., from GeotechTools.org). Although several of the references appear to be relatively old, they are not necessarily dated. The cost of the geosynthetic materials have not increased very much over the past several decades, and, in some cases, they have actually decreased, while the prices of other civil engineering materials have generally increased (e.g., select granular aggregates have more than doubled in some regions of the world due to restrictions on excavation of natural materials). Therefore, the use of older cost studies likely underestimates the actual savings that can be achieved.

2 REDUCTION OF SELECT SOIL MATERIALS

Geosynthetics often replace other select soil and rock materials at a material and installation cost that is lower than the natural material alternative. This is the primary reason that geosynthetics were originally used. For example, in hard armor erosion control applications, one of the first applications of geosynthetics, a geotextile filter is placed below hard amour rip-rap, replacing a 150 mm or greater thick layer of select graded granular filter material. Unless the granular material is available at the site, with the correct gradation, or the rip-rap alone will work (which is seldom the case), the geosynthetic including its installation is always less expensive (i.e., by about 50% of the installed graded granular filter cost) (Holtz et al, 2008). Geosynthetics are also often used in geotechnical systems and, due to improved efficiencies in performance, may decrease the volume of other geotechnical materials used in that system. For example, in haul road construction over soft soils (shear strength < 30 kPa), geosynthetics have been shown to directly decrease the amount of aggregate required by 30 to 40%. Again, the cost of the geosynthetic is most often lower than the cost of the aggregate saved.

As the cost savings in these applications are obvious, the decision to use a geosynthetic is straightforward. In fact, in many of these applications the cost benefit is so apparent that the use of geosynthetics is now the standard of practice (e.g., geotextile filters in erosion control and geotextiles for stabilization of soft soils in haul road construction). The following provides a brief review of several other geosynthetic applications where immediate cost savings from reduction of requirements for select soil materials is apparent.

2.1 *Geotextile Filters in Drainage Applications*

In the case of geotextiles used as a filter to wrap an edge drain trench, the geotextile allows for a reduction in the size of the trench. Before geotextiles were used in this application, either a granular filter was required to be placed around the open graded drainage aggregate or a well graded material was used to both act as a filter and provide drainage. Both alternatives required a relatively wide trench, typically 0.6 m to 0.8 m wide, either to provide additional space for the graded granular filter or to obtain a sufficiently large welted perimeter in order to provide the same drainage as more open, higher permeability gravel.

The use of a geotextile filter wrapped around open-graded aggregate results in improved inflow efficiencies allowing for considerable reduction in the physical dimensions of the drain trench without a decrease in flow capacity (typically on the order of 0.3 m in width). The cost savings from the reduction in the volume of the excavation and the volume of filter material required are significantly more than the cost of the geosynthetic. For example, in the US, the 2012 bid prices of geotextiles used as filters obtained from transportation agencies' web sites were on the order of \$0.50[1]/m^2 to \$1.50/m^2 (Christopher, 2013). Higher costs should be anticipated for below-water placement. As previously noted, geotextile prices have not risen significantly over the last 20 years, however gravel cost has. The same web pages used for the cost of geotextiles showed prices of select granular materials ranging from \$3.00/m^2 to \$10.00/m^2 for a 75 mm to 150 mm thick granular layer, which is typical of the volume of graded aggregate that will be replaced with the geosynthetic. Again, this obvious cost benefit has resulted in the use of geotextile filters as the standard of practice for subsurface drainage application.

2.2 *Geosynthetic Reinforced Soil Walls*

Geosynthetic reinforced soil (GRS) walls are practically always less expensive than conventional reinforced concrete and gravity type (e.g., crib and bin walls) earth retaining systems due to lower overall system material costs. Using geogrids or geotextiles as reinforcement has also been found to be 30 to 50% less expensive than other metallic reinforced soil construction with concrete facing panels, especially for small to medium sized projects (Allen and Holtz, 1991). A cost comparison for GRS walls versus other types of retaining walls is presented in Figure 1.

Much of the savings over reinforced concrete cantilever walls are due to the low cost of the geosynthetic reinforcement, the strength and corresponding cost of which increases linearly with height. For concrete cantilever walls, the steel reinforcement and concrete thickness required for stability increases exponentially with height. As a result, modular block faced walls with geosynthetic reinforcement are competitive for low height walls and very competitive as the height increases as shown in Figure 1. In general, the use of geosynthetic reinforced soil walls results in savings on the order of 25% to 50% of the cost of a conventional reinforced concrete retaining structure (Berg et al., 2009). Due to their flexibility and ability to accommodate a relatively large total and differential settlement, substantial savings are often obtained by elimination of the deep foundations required for conventional reinforced concrete structures at sites with poor foundation conditions. In such cases, the elimination of costs for foundation improvements such as piles and pile caps, that may be required for support of conventional structures, have resulted in cost savings of greater than 50% on completed projects.

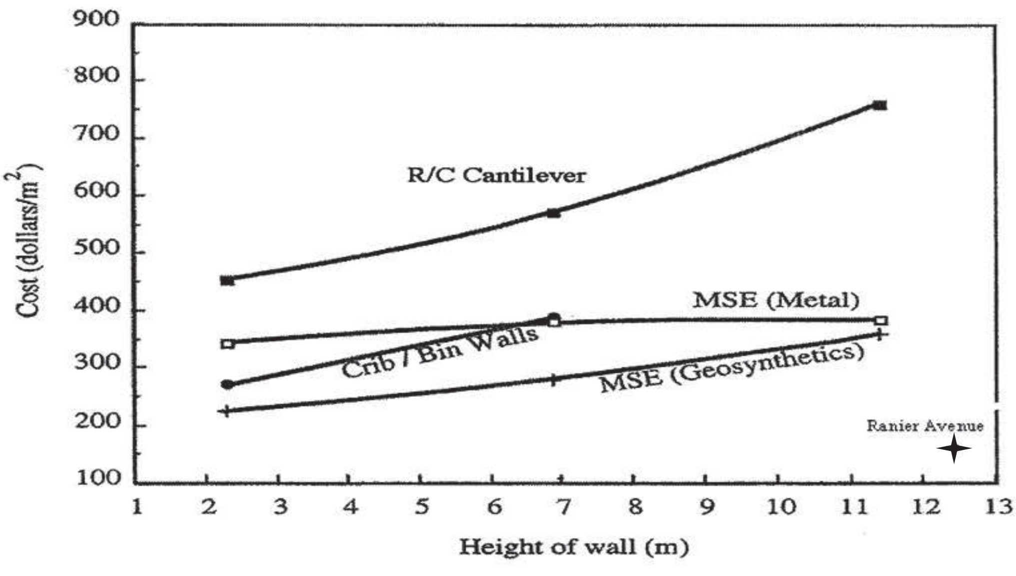


Figure 1. Cost comparison of reinforced systems (Holtz et al., 2008, after Koerner et al., 1998)

[1] All costs in this paper are in US\$

Concrete facing panels and steel reinforcements are also more expensive than modular block facings and geosynthetic reinforcements for low to moderate height walls as shown in Figure 1. Modular block faced walls at heights less than 4.5 m are typically less expensive than segmental panel faced walls by 10% or more. Typically the reinforcing cost is 15 to 30% of the total cost of a geosynthetic reinforced soil wall, depending on the face construction cost (Berg et al., 2009). For example, at the joint US Federal Highway Administration (FHWA) and Colorado Department of Highways' Glenwood Canyon wrapped faced geotextile test walls with a shotcrete finish (Bell et al., 1983), the cost of the geotextile was only about 25% of the total wall cost.

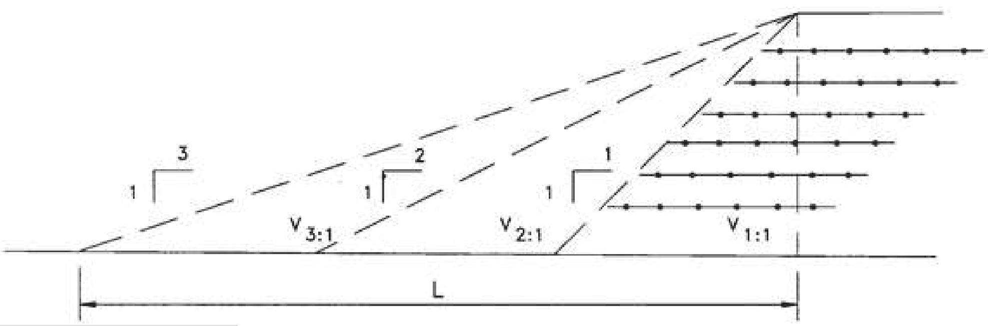
GRS walls may be most cost effective in temporary or detour construction (e.g., see the cost of the Rainer Avenue wall indicated in Figure 1), and in low-volume road construction (*e.g.*, national forests and parks). At the time of its construction, the Rainier Avenue wall was one of the highest geotextile walls ever constructed (Allen, et al., 1992). The wall, a temporary wrapped faced geotextile reinforced soil wall, was constructed to provide a surcharge for a bridge foundation, and no special facing was required. Permanent facing on a wall of that height would have increased its cost by $\$50/m^2$ of wall face or more (Holtz et al., 2008).

2.3 *Geosynthetic Reinforced Soil Slopes*

Reinforced soil slopes (RSS) are cost-effective alternatives for new construction and reconstruction where the cost of fill, right-of-way, and other considerations may make a steeper slope desirable. In the case of repairing a slope failure, the new slope will be safer, and reusing the slide debris rather than importing higher quality backfill may result in substantial cost savings. RSS also provide an economical alternative to retaining walls. In some cases, reinforced slopes can be constructed at about one-half the cost of GRS walls. The use of vegetated-faced RSS that can be landscaped to blend with natural environments may also provide an aesthetic advantage over retaining wall structures.

High RSS structures have relatively higher reinforcement and lower backfill costs. Recent US bid prices suggest costs ranging from $\$110/m^2$ to $\$260/m^2$ of projected vertical slope face as a function of height, with applications in the 10 to 15 m height range costing about $\$170/m^2$ (Berg et al., 2009 and GeotechTools.org, 2012), excluding safety features and drainage details. For example, two RSS projects reported by Berg et al. (2009) had the following structural characteristics and costs: 1) Salmon Trail Pass constructed to a height of 15 m at a face slope of approximately 1H:1V with geotextile reinforcement had a cost of $\$160/m^2$ of projected vertical slope face, and 2) Dickey Lake constructed to maximum slope height of 18.3 m at a face slope as steep as 0.84H:1V with geogrid reinforcement had a cost of $\$180/m^2$ of projected vertical slope face. Comparing these costs to Figure 1 for similar height GRS structures confirms a clear cost advantage of RSS.

A rapid, first-order assessment of cost items for comparing a flatter unreinforced slope with a steeper reinforced slope is presented in Figure 2. Evaluating the cost as shown in the figure, if the backfill material for a 3H:1V unreinforced slope cost $\$5/m^3$, a 1H:1V geosynthetic RSS can be constructed at about the same cost as the 3H:1V slope, and that does not include the cost of the land saved by building the steeper slope. In urban and suburban environments where the land cost is expensive and fill soil cost is at a premium, RSS offer a significant cost saving.



Volume of Soil, V		COST:
$V_{3:1} = V$	$V_{3:1} = L$	3H:1V = $V_{SOIL} + L_{LAND}$ + Guardrail* (?) + Hydroseeding (?)
$V_{2:1} = \frac{2}{3}V$	$V_{2:1} = \frac{2}{3}L$	2H:1V = $\frac{2}{3}V_{SOIL} + \frac{2}{3}L_{LAND}$ + Guardrail + Erosion Control + High Maintenance
$V_{1:1} = \frac{1}{3}V$	$V_{1:1} = \frac{1}{3}L$	1H:1V = $\frac{1}{3}V_{SOIL} + \frac{1}{3}L_{LAND}$ + Reinforcement + Guardrail + Erosion Control
		* Include guardrail or traffic barrier cost if required.

Figure 2. Cost evaluation of reinforced soil slopes (Elias and Christopher, 1997).

2.4 *Geosynthetics Used for Constructing Reinforced Soil Embankments*

For very weak soils, geosynthetics used in reinforced soil embankments reduce the amount of displacement of the foundation soil that would occur in construction of unreinforced embankments (see Figure 3). Cost for geosynthetics (i.e., geotextiles or geogrids) in this application typically range from approximately $3/m^2 to $15/m^2, while the granular fill material typically used for embankment construction ranges from $5 to $20/m^3 based on bid prices from geotechtools.org, 2012).

The amount of fill saved often offsets the cost of the reinforcement and additional cost savings is usually achieved through expedient embankment construction when using geosynthetic reinforcement (reviewed in Section 3). The amount of fill saved will depend on the strength of the foundation soil, but in very weak soils it can easily be a meter or more. In the extreme cases where displacement techniques are used for the unreinforced embankment (i.e., Figure 3b), volumes equal to or greater than the embankment volume can be lost into the soft subgrade soil. For example, in construction of dikes at Craney Island, Virginia, USA, without reinforcement 8 to 10 volumes of soil were lost as it was pushed down into the soft soil in order to build 1 volume above the surface (Fowler, 1989). Reinforced embankments were constructed on that project with less than 1 volume lost for 1 volume above the surface and in cases where there were dry soil crust layers, only 0.3 m were lost in constructing 3.1 m high dikes.

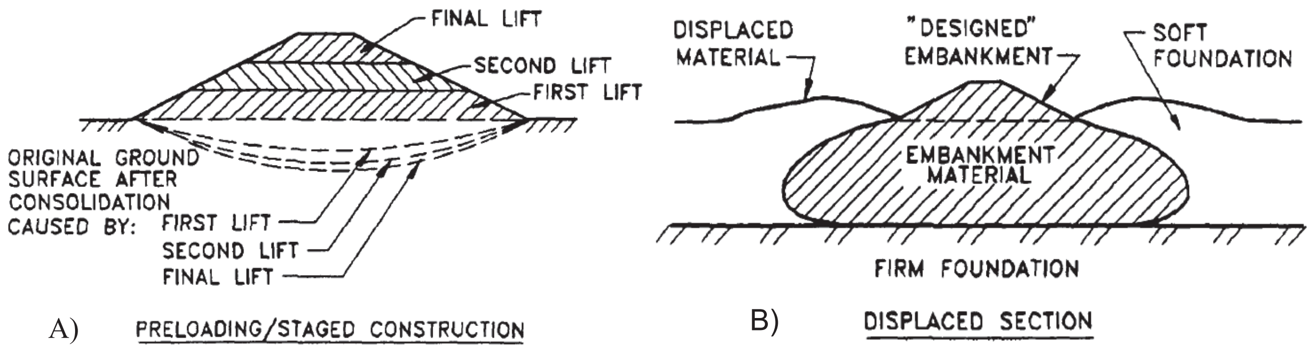


Figure 3. Displacement during conventional unreinforced embankment constructions (Fowler, 1989)

2.5 *Geosynthetic in Waste and Other Containment Systems*

The most significant cost savings related to material replacement are for geosynthetics used in landfill applications and, to a lesser extent, other containment systems (e.g., water reservoirs). Material and in-place costs will obviously vary with the type of geosynthetic barrier and the quantity of barrier specified. In-place cost of geosynthetic barriers can vary from approximately $3.00/m^2 to $19.00/m^2. Cost of conventional compacted clay liners can vary between approximately $6.00/m^2 to $30.00/m^2 per meter depth in-place, depending on the availability and hauling distance. However, in these applications, the savings are not just from the cost difference between the geosynthetic and the replaced material, but more significantly from the value of the volume of space saved by using very thin geosynthetic materials to replace the much thicker alternative barrier systems. In landfills, one cubic meter of volume is often worth $20 for municipal waste and up to $100 for hazardous waste. A geomembrane barrier typically replaces 1 to 2 m of a clay barrier layer and a geotextile filter or cushion layer typically saves 0.15 m of a granular layer for each layer it replaces.

3 EASIER AND/OR ACCELERATED CONSTRUCTION COST-BENEFIT

Installation of the geosynthetic is usually easier than placing and compacting the soil materials that they replace. For example, in the case of geotextile filters used as substitutes for graded granular filters (discussed in the previous section), the geotextile filters are much easier to place, especially below water where graded filters require very careful placement procedures to avoid segregation. It is difficult to assign a cost savings to this simple example and the actual savings appear to be secondary to the savings in alternate construction materials. However, in some cases, the easier and speedier construction is paramount to the use of a geosynthetic. The following provides a review of several applications where this type of cost-benefit is apparent.

3.1 *Geosynthetic Geocomposite Drains*

Prefabricated geocomposite drains, used to replace or support conventional graded aggregate and pipe drainage systems, offer a readily available material with known filtration and hydraulic flow properties, easy installation, and, therefore, construction economics (Hunt, 1982). Costs of prefabricated drains typically range from \$7.50 to \$10.00/m^2. The high material cost is usually offset by expedient construction and reduction in required quantities of select granular materials. For example, geocomposites used for pavement edge drains typically cost \$3.00 to \$10.00/linear meter installed while a conventional geotextile wrapped gravel drain with a pipe is on the order of \$30.00/linear meter installed (Berg et al., 2009).

3.2 *Geosynthetics Used for Constructing Reinforced Soil Embankments*

Cost savings from using reinforced soil embankments for construction over soft soils are also related to increased speed of construction. In a review of 40 reinforced embankment case histories, Humphrey and Holtz (1986) and Humphrey (1987) found that in many cases, the failure height predicted by classical bearing capacity theory was significantly less than the actual constructed height, especially if high strength geotextiles and geogrids were used as the reinforcement. Comparing the embankment height versus average undrained shear strength of the foundation, trend lines through the height of the failed reinforced soil embankments and height of the failed unreinforced soil embankments clearly showed that the embankment height could be increased by about 2 m by using reinforcement. The ability to safely construct greater embankment heights, in addition to providing a more stable working platform, allows more rapid construction of the embankment, increased embankment heights for staged construction and, in both cases, faster consolidation of the subgrade due to the application of greater surcharge loads.

3.3 *Column Supported Embankments (CSE) with a Geosynthetic Reinforced Load Transfer Platform*

When time constraints are critical to the success of the project, instead of constructing an embankment and waiting for consolidation, column supported embankments (CSE) with a geosynthetic reinforced load transfer platform can be constructed. CSE are designed to transfer the load of the embankment through the soft compressible soil layer to a firm foundation. Thus, the construction wait time for dissipation of pore water pressures and minimizing settlement of the foundation soils is eliminated. The geosynthetic reinforcement increases the spacing requirement for the columns, reducing the material cost similar to the cost savings discussed in Section 2, as well as increasing the speed of construction corresponding to the reduction in CSE installation time. This technology was first used in Sweden in 1971 (Holtz et al., 2008), and has been used successfully on projects around the world since the early 1990s.

The key advantage to CSE is that construction may proceed rapidly in one stage. Total and differential settlement of the embankment may be drastically reduced when using CSE over conventional approaches or reinforced embankments. As with geosynthetic reinforced embankments, there are cost savings by eliminating displacement. However, while the initial construction cost of CSE is much higher than reinforced or conventional embankment construction, the reduction in construction time can usually result in a total construction cost that is far less than that of other solutions.

3.4 *Geosynthetic Reinforced Soil Walls with Integrated Bridge Structures (GRS-IBS)*

A limited number of small bridge projects have been successfully constructed around the world using geosynthetic reinforced soil walls in combination with precast bridge components. The successful performance of these structures, in addition to demonstrated reduced bridge construction time and cost, has caught the attention of federal agencies. Recently, within the past five years, there has been a major effort made by the US Federal Highway Administration (FHWA), as part of their everyday counts initiative, to promote and support the use of geosynthetic reinforced soil walls for the support of simple bridge structures by local and state transportation agencies. Part of the impetus for this effort has been recently completed research, along with design guidance developed by the FHWA's research laboratory, to integrate the bridge structure directly into the GRS abutment wall. Using the GRS wall to directly support the bridge either eliminates or significantly decreases foundation support requirements (i.e., eliminates deep foundations) and provides a significant decrease in the time required to construct the completed bridge structure (Adams et al., 2011 and 2012).

The primary reason for this effort is that previously very few agencies would consider geosynthetic reinforced soil walls for this application, but in the past five years, over 160 structures have been constructed or are in the design stage in 35 US states. Based on the completed structures, FHWA has found that bridges constructed with GRS-IBS cost 25 to 60% less than bridges built with traditional methods, depending on the standard of construction and the method of contracting (local forces versus a private contractor). Much of these savings come from the elimination of deep foundations and the completion of the bridge structures in weeks versus months for traditional bridge structures. A long-term GRS-IBS benefit that has been observed on practically all structures completed to date is the mitigation of the "bump at the end of the bridge" problem caused by differential settlement between the bridge abutment and the approaching roadway. This should significantly reduce maintenance costs, but more time will be required to adequately assess the actual savings.

One example of a completed GRS-IBS is a small bridge project with a span length of less than 15 m and rated at less than 18 metric tons capacity constructed in Huston Township, Clearfield County, Pennsylvania, USA (Albert, 2011). The actual cost of the bridge project was $102,000 and the cost savings were estimated at $48,000. Also, the entire project was constructed in 10 days start to finish, where normally it would have taken more than a month.

A 32 m long single span bridge with a 30 degree skew and abutment heights of 6 m was recently constructed over the Housatonic Railroad in Sheffield, Massachusetts, USA. That structure had a bid price of $1,163,00 and was estimated to have saved $1,136,000 (i.e. 49%) over the original design, which was a micropile-supported structure (Tobin, 2014).

One of the more significant bridge structures constructed to date involved replacing twin bridges located on the westbound and eastbound routes of Interstate 84 (I-84) over Echo Frontage Road in Summit County, Utah, USA (about 80 km east of Salt Lake City). The two interstate bridges had 17.6 m span lengths and weighed about 800,000 kg apiece. Using the GRS-IBS system and precast concrete components for the bridge decks helped reduce the construction time considerably for this important interstate corridor. The economic analysis included construction time and cost, user costs, delay cost, and safety cost and resulted in a total cost of approximately $4.3 million, which was $300,000 less than the alternate design approach. In this case, all of the savings came from the significant decreased user cost as the delay cost for the public was only 34 hours, with some additional similar delay cost due to speed reduction, versus 194 days for the traditional design alternative (Alzamora, 2014).

4 IMPROVED LONG-TERM PERFORMANCE

Most of the applications which use geosynthetics are designed to perform equally to the alternate design solutions. However, we now have a performance history of several decades or more for a number of applications where there are good indications that the geosynthetic solutions have improved performance over alternate traditional designs. Part of the reason, as many have anticipated, is that geosynthetics often actually work better than the geotechnical materials they replace (e.g. see Section 2 for the materials they replace). The performance improvement is gained by using manufactured materials with known properties (i.e., geosynthetics), as compared to the relative high variability of the soil materials they replace. In some applications, geosynthetics also improve the performance of geotechnical materials (e.g., adding tensile strength to materials that have none).

The potential for long-term performance improvements is often, and rightfully so, touted as a significant benefit for using geosynthetics; however, as indicated in the introduction, quantification of the actual performance heretofore has been relatively elusive. The following provides several examples where this benefit has come to fruition, has been documented, and is supported with cost information.

4.1 *Geosynthetic Separators in Pavement Construction*

The ability to separate two dissimilar materials (i.e., the subgrade and granular structural layers in the pavement system) is a basic function of geotextiles. When subgrade soils are relatively weak, separation is typically obvious as contamination and loss of granular soils often occur during construction. Even when roadways are constructed of firm, fairly competent subgrades (CBR ranging from 3 to 8), but containing a high quantity of fines (particles finer that 0.075 mm), subgrade intrusion can also occur under long term dynamic loading. This is particularly a concern for soils that are seasonally weak (e.g., from frost heave) or soils susceptible to pumping during wet periods, especially when open-graded base courses are used.

Significant fines migration has been observed with a subgrade CBR as high as 8 (e.g., Al-Qadi et al., 1998). It only takes a small amount of fines to significantly and adversely affect the structural characteristics of select granular aggregates (e.g., see Jornby and Hicks, 1986). Therefore, separation is important to maintain the design thickness, the base course material integrity, and drainage capabilities. Thus, the geosynthetic will ultimately increase the life of the roadway. However, where the subgrade is relatively firm, the geosynthetic separator (typically geotextiles) may not be required for improved stability for construction and thus its use adds a cost increase to the project. In these cases the use of the geosynthetic is solely based on long-term improved performance. Although the benefit is somewhat apparent, as this cost saving has not been well documented, this application is significantly underutilized.

With the significant history of the use and advancement of geosynthetics, numerous research efforts are ongoing to quantify the cost-benefit life cycle ratio of using geosynthetics in permanent roadway systems (e.g., Yang, 2006). However, from a cost point of view, it does not need to increase the life very much to provide a return on the investment in using a geosynthetic separator. Relatively lightweight geotextiles that are only strong enough to survive construction are used in this application, and are relatively inexpensive. Based on 2012 bid prices in the US, the in-place cost of a separation geosynthetic is generally on the order of \$1.20/m^2. The cost of the pavement section is generally \$30/m^2 to \$120/m^2, which implies that the geosynthetic cost ranges from less than 1% to up to 5% of the initial construction cost.

Using a separation geotextile simply to prevent long term contamination of the structural layers can easily extend the life of a pavement by more than 5% (approximately 1 more year for a 20 year performance period), which will more than make up for the cost of the geosynthetic. In fact, in many studies, the geotextile separator is estimated to extend the life of the pavement by more than 50%, potentially returning many times the investment in the geosynthetic (Al-Qadi et al., 2007). One study in Virginia on monitored pavement sections found an anticipated improvement of over 100 % in traffic loading for sections with geotextile separation layers as compared to control sections (Bhutta, 1998; and, Al-Qadi and Appea, 2003).

Perhaps of greater value, the geosynthetics at the subgrade-base interface and/or within the base increase the reliability of the base and subgrade support, allowing rehabilitations of the riding layer (i.e., asphalt) and extending pavement life before complete reconstruction is required. A competent subgrade/base support is critical to realizing life-cycle cost benefits of surface rehabilitation over the life of a pavement structure.

4.2 *Geosynthetics for Stabilization of the Subgrade for Pavement Construction*

As reviewed in Section 2, the cost of using geosynthetics for stabilization is practically recovered from aggregate savings alone. However, there are also long-term cost benefits related to improved performance, including the ability to prevent premature failure of the subgrade, prevent contamination of the base (as discussed in the previous section on separation) and/or improve base course support, essentially providing low-cost insurance that planned surface rehabilitations can be performed when the design pavement life is reached. These life cycle cost benefits become very important, when comparing mechanical stabilization with geosynthetics to other stabilization methods such as chemical stabilization (e.g., with lime or cement) (e.g., see Al-Qadi and Yang, 2007).

Estimation of construction costs and life cycle benefit-cost ratios for geosynthetic-stabilized road construction is straight forward and basically the same as that required for alternative pavement designs. In addition to the cost of materials and construction, maintenance, and rehabilitation, the method should also include user costs during each of these activities. Both user costs during normal operations as well as user benefits resulting from the project should be considered. Life-cycle cost analysis models for evaluating long term pavement performance such as the US Federal Highway Administration's program RealCost (available at http://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm) or similar programs should be used to calculate comparative cost over several performance periods to encompass the full life of the pavement. An example using this program will be reviewed in the next section.

In this application, stronger geosynthetics are required than those used for separation alone, thus the cost of the material is somewhat increased. Bid prices for stabilization geosynthetics are typically on the order of \$1.20 to \$3.60/m^2. Cost tradeoffs should also be evaluated for different construction and geosynthetic combinations. This should include subgrade preparation and equipment control versus geosynthetic survivability. In general, stronger, higher survivability geosynthetics will have a higher material cost; however, higher survivability materials may result in less expensive construction cost due to the additional subgrade preparation and care in placement necessary to use lower-survivability geosynthetics.

The cost savings identified for separation in Section 4.1 also apply to stabilization, as separation is one of the principal functions in stabilization applications. Geotextiles directly provide the separation function, along with filtration and reinforcement. For geogrids, separation is performed by either using an aggregate layer, which is sized to adequately filter the subgrade fines, or by using a geotextile separation layer with the geogrid, either of which must be considered in the stabilization layer cost.

Again, it is noted that competent subgrade/base support is critical to realizing life-cycle cost benefits of surface rehabilitations over the life of a pavement structure. Al-Qadi and Yang (2007) provide a life cycle cost analysis on 25 preventive pavement design alternatives using two different geosynthetic design methods, one for stabilization and one for reinforcement (as discussed in the next section) and show the influence of the design method on the user cost. Both methods show cost benefit, however, the results vary considerably for the pavement design alternatives.

4.3 *Geosynthetic Base Reinforcement*

Geosynthetics (i.e., geogrids, geotextiles, geocomposites or geocells) can also be used to reinforce the base course of flexible pavement to improve its serviceability. In base reinforcement applications, the geosynthetic is placed within or at the bottom of unbound layers of a flexible pavement system and improve the load-carrying capacity of the pavement under repeated traffic. The current design practice and the recent developments for the use of geogrids in base reinforcement applications are discussed by Perkins et al., 2010. As reported in that paper, field and full-scale tests show that reinforcement clearly improves the performance of a pavement. A number of studies have demonstrated that the service life of the pavement, as defined by the number of load repetitions carried by the pavement to reach a particular permanent surface deformation, can be increased by a factor ranging from just over 1 (i.e., no improvement) to in excess of 100 by the inclusion of a geosynthetic in the base aggregate layer.

Studies have also shown that base course thickness can be reduced by up to 50% by the inclusion of a geosynthetic. Most studies have quantified benefit in terms of pavement rutting. However, there are very few documented case histories of actual projects, and none that can clearly identify the true cost benefit, mainly because this application is relatively new and there are no applications where the projects have reached their design life. However, the benefit can be calculated using life-cycle cost analysis models for evaluating long term pavement performance, such as the previously mentioned program RealCost or similar programs. The following example from Holtz et al. (2008) uses the RealCost program and the few available case histories, the field studies referenced above, available design methods and hypothetical evaluation to obtain an idea of the true cost benefit of using geosynthetics for the particular project conditions. Three alternates are considered:

Alternate I: An unreinforced control pavement section.
Alternate II: Geosynthetic reinforcement used to extended life of the pavement (i.e., additional vehicle passes).
Alternate III: Geosynthetic reinforcement used to reduced base aggregate thickness (i.e., reduced undercut, aggregate quantities and initial construction cost).

Design was based on AASHTO, 1993 Design Guide for the unreinforced section and AASHTO PP 46-01 Standard of Practice, Geosynthetic Reinforcement of the Aggregate Base Course of Flexible Pavement Structures for the reinforced sections. Complete design is covered in Holtz et al. (2008). The final design is shown in Table 1 for each alternative and the comparison of the initial construction costs for Alternative I (unreinforced road) and Alternative II and III (geogrid-reinforced road) is done for the cost of materials in Table 2, which were based on local sources.

Table 1. Summary of Pavement Design for each Alternative

Design Option	Alternative I Unreinforced	Alternative II Performance Period Extension with Geosynthetic	Alternative III Reinforced with reduced section
Design ESAL	1,000,000	4,000,000	1,000,000
Performance Period (yrs)	20 w/ 10 yr repair	40 w/ 20 yr repair	20 w/ 10 yr repair
Pavement Option			
ACC Surface	25 mm	25 mm	25 mm
ACC Binder	64 mm	64 mm	64 mm
Base Course	280 mm	280 mm	178 mm
Subbase Course	150 mm	150 mm	150 mm
Geosyn. Reinforcement	none	yes	yes
— In-Place Cost	n/a	4.25	4.25
— TBR Value	n/a	4	4
Design ESAL	1,000,000	4,000,000	1,000,000
Performance Period (yrs)	20 w/ 10 yr repair	40 w/ 20 yr repair	20 w/ 10 yr repair

The analysis of the initial construction costs indicate that the geogrid-reinforced alternative (III) leads to overall savings of 6.4% relative to the unreinforced Alternative I, while Alternative II would actually cost more than the initial construction cost of the unreinforced section. However, the results of the long-term cost benefit analysis shown in Table 5 provide a more complete picture of the true cost savings. In this case, Alternative II provides a 10.5% savings as compared to the unreinforced Alternative (I), while Alternative III provides an overall savings of 4.5%, demonstrating that life cycle cost analysis should be performed to fully recognize the cost benefit of geosynthetics.

Table 2. Material Cost

Layer	Material Type	Cost* ($/tonnes)	Cost ($/m^3)
1	Asphalt wearing course	61.00	140.00
2	Asphalt binder	61.00	140.00
3	Aggregate base course	24.00	46.50
4	Subbase course	13.00	28.50
5	Biaxial Geogrid (incl. installation cost)	$5.00/m^2	

* Average cost in 2008 from a Southeast DOT

Table 3. Summary of initial construction costs for 1-km of road for Alternatives I, II and III.

Expenses	Alternative I: Unreinforced	Alternative II: Geogrid-reinforced	Alternative III: Geogrid-reinforced
Asphalt	$161,700	$161,700	$161,700
Aggregate base	$181,200	$181,200	$115,300
Subbase	$43,200	$43,200	$43,200
Geogrid	$0	$41,700	$41,700
Undercut/Fill	$0	$0	$0
Total Costs	$386,100	$427,800	$361,900
Unit Costs	$50.70/m^2	$56.20/m^2	$47.50/m^2

Table 4. Parameters Used in Life-Cycle Cost Examples

Parameter	Value
Initial Serviceability	4.2
Terminal Serviceability	2
Reliability Level	95
Overall Standard Deviation	0.49
Subgrade Resilient Modulus	40 Mpa
Structural Design Number	3.72
Maintenance — Annual cost initiates 5 yrs after construction or rehabilitation	$160/lane km
Discount Rate	3.50
Evaluation Method	NPV
Salvage Value	0

Table 5. Summary of Pavement Design for Life-Cycle Cost Analyses

ESAL/Analysis Period		2,200,000 / 40 years	
Design Option	**Alternative I Unreinforced**	**Alternative II Performance Period Extension w/geosynthetic**	**Alternative III Reinforced w/ reduced section**
Initial Construction Cost ($/km)	$386,100	$427,800	$361,900
Total Life-cycle[a] Cost ($/km)	539,700	483,200	515,600
Percent Savings Compared to Unreinforced Design	—	10.5%	4.5%

Note: a. In 2008 dollars.

4.4 *Geosynthetic in Pavement Overlays*

One of the most widely used applications of geosynthetics is in asphalt overlays of asphaltic concrete pavements for rehabilitation of roads. Three different geosynthetics are used in these applications, including nonwoven geotextiles, geogrids and geocomposites.

Nonwoven geotextiles provide a stress-relieving interlayer in which the stresses are dissipated at the joint or crack before they create stress in the overlay. In addition, the geotextile is saturated with tackcoat and thus provide a moisture barrier that protects the underlying pavement structure from further degradation due to infiltration of surface water even after the reflective cracks have returned. Geogrids are used to provide a stress-resistance layer in which a high tensile modulus reinforcement is used to resist tensile stress in the new HMA overlay. Finally, multilayer geocomposites may provide elements of both approaches.

4.4.1 *Geotextile stress-relieving interlayer*

The geotextile stress-relieving interlayer has the longest history of use with the first installation in the late 1960s. The installed cost of the geotextile interlayer system includes the cost of the geotextile, the additional tackcoat to saturate the geotextile, and installation. The design thickness of an AC overlay with a geotextile interlayer should be determined as if the geotextile is not present. The economic justification of geotextile use is then derived from either or both (Holtz et al., 2008):

- An increase in pavement life, a decrease in pavement maintenance costs, and an increase in pavement serviceability due to retardation and possible reduction of reflection cracks.
- An increased structural capacity due to drier base and subgrade materials.

Increased life of the overlay also lowers vehicle operating costs due to higher levels of serviceability and lowers user delay costs due to future preventive and rehabilitative maintenance interventions (Tighe et al., 2003 and Amini, 2005), which should also be included in the economic analysis of these treatments.

The old pavement surface condition and overall installation play a very important role in the performance of the paving geotextile. Under favorable conditions, reflection cracks can be impeded for approximately 1 to 5 years, as compared to the overlay without the paving grade geotextile. The broad range is directly related to the load levels and magnitude of deformation at the joint or crack. The anticipated life improvement, under favorable conditions (i.e., fatigue type alligator cracks no wider than 3 mm, small joint or crack movement of less than 0.2 mm, and no thermal or structural issues), is approximately 100% to 200% that of an overlay of the same design thickness without a geotextile.

Other cost benefits, currently not quantified, include the geotextile interlayer functioning as a moisture barrier and the potential improvement in ride quality and aesthetics. The effect of the geotextile on the quality of drainage might be used to objectively estimate an increase in pavement structural capacity. This increased capacity then can be used to estimate increased pavement life or to design a thinner AC overlay. These potential economic benefits may be combined for a particular project.

Extensive research conducted by Caltrans (Predoehl, 1990), implies that a geotextile interlayer is equivalent to 30 mm of asphalt concrete for relatively thin (i.e., $\leq$ 120 mm) overlays that are structurally adequate. This equivalent value was confirmed in the study by Maxim Technologies (1997), which reviewed the results of over 100 pavement sections (AC and PCC) on which performance of the HMA overlay system with and without geotextiles was monitored. The Maxim study also developed a pavement design model with consideration for both the environmental and structural effects. Their analysis indicated a total average effect of 33 mm with 13 mm environmental equivalent thickness benefit and 20 mm structural equivalent thickness benefit. This equivalent value is significantly greater that the in-place cost of the overlay geotextile, which is roughly equivalent to the cost of about 15 mm of asphalt concrete (Holtz, et al., 2008).

Considerable insight into the economics of overlay design with geotextiles can be gained from historic cost and performance data (Barksdale, 1991) such as the study by Maxim Technologies (1997). A number of regional studies have also been developed. Many of these and the associated reports can be found on the internet. Examples include:

- "Study of Pavement Maintenance Techniques used on Greenville County Maintained Roads" (Sprague, 2005) in which overlay treatments on 370 roads were evaluated for a 6 year period of time (available at: www.gmanow.com).

- A synthesis of practice by the Mississippi Department of Transportation in cooperation with FHWA titled "Potential Applications of Paving Fabrics to Reduce Reflective Cracking" (Amini, 2005). (available at: http://www.gomdot.com/research/pdf/PavFabr.pdf).
- "Geosynthetics in Flexible and Rigid Pavement Overlay Systems to Reduce Refection Cracking" (Cleveland et al., 2002). (available at: http://tti.tamu.edu/documents/1777-1.pdf).

Using bitumen saturated geotextiles in chip seal applications has also been found to provide a significant cost savings. Brown (2003) studied field trials and experimentation of double chip seal with geotextiles over a period of 19 years and found that this treatment substantially adds to the pavement life through the retardation of reflection cracks and water/air proofing, at a lower cost than other standard overlays. He noted that the treatment reduced further deterioration of the old pavement due to oxidation and stripping, and reduced crack reflection more than other conventional methods including asphalt overlays with paving fabric.

Two cost benefit studies have been performed in California by local transportation authorities. The first study found no reflective cracking after 17 years of service in a low volume road where chip seals were placed over geotextiles. A life cycle cost analysis showing the cost effectiveness of these pavement sections versus other types of treatment is reported by Davis, 2005 (available at www.trb.org/publications/circulars/ec078.pdf). The second study was performed by the county of Sacramento Department of Transportation titled "Chip Seal over Fabric Excelsior Road" in which geotextiles with two different binders under a variety of chip seals were evaluated over a 6-year period of time (available at: www.aia-us.org/docs/SacramentoCountyChipOverFabricReport.pdf).

4.4.2 *Geogrid stress resistant reinforcement*

Geogrid stress resistant reinforcement does not have the history of use as geotextiles in overlay applications. The cost of geogrid reinforcement is relatively high compared to geotextiles and adds substantially to the cost of an overlay. However, the potential performance may provide a significant cost-benefit. Based on beam testing of three reflection crack treatments, Caltabiano and Brunton (1991) developed the relative cost comparison of various overlay treatments shown in Table 6 (Brown, 2006). This information indicates that geosynthetics (both geotextiles and geogrids) were more effective than the polymer modified asphalt. Other laboratory and field studies support these findings. For example, Hessing and Thesseling, 2013 reported two field studies with excellent performance with no cracks observed in the geogrid reinforced overlays after 5 to 7 years, while significant cracking was observed in unreinforced sections over that same period. However, life cycle cost field studies are limited due to the more recent initiation of this application.

Table 6. Cost Considerations (Caltabiano and Brunton, 1991 as reported by Brown, 2006)

Overlay	Relative Life	Relative Costs
Standard asphalt	1.0	--
Polymer modified asphalt	2.5	2.5
Geotextile	5.0	1.0
Geogrid	10.0	2.0

4.4.3 *Geocomposite stress relieving/resistant interlayer*

Geocomposites tend to provide the best performance in these applications, combining the benefits of both geotextiles and geogrids. However, the cost of geocomposites is relatively high (on the order of $\$4/m^2$ to $\$16/m^2$ installed. As a result of the high material cost, they are often used in narrow strips to provide an effective local treatment. Again, life cycle cost studies are limited due to the recent introduction of this application and, as a result, the cost-effectiveness of this approach has not been clearly established.

4.4.4 *Economic analysis issue for pavement overlays*

A final economic analysis issue is the probability of success. Geosynthetic interlayers, as well as other rehabilitation techniques, are not always effective in improving pavement performance, especially in cold regions where thermal cracking is an issue. Therefore, an estimate of the probability of success should be included in all economic analyses (Barksdale, 1991). The probability of success will obviously increase with thoroughness of rehabilitation design, favorable pavement conditions, local experience with geotextile interlayers, and thoroughness of construction inspection.

4.5 *Geosynthetic in Containment Systems*

The most significant long-term savings by using geosynthetics in containment systems is in extending the life of the facility by having more volume (e.g., for waste disposal in landfills and potable water in retention ponds). As indicated in Section 2.6, containment volume is increased due to the reduction in space occupied by the liner; however, additional volume can also be achieved due to improved performance gained by replacing the clay with more stable geotechnical materials and using geosynthetics with high interface properties (e.g., roughened sheet geomembranes). These improvements allow for the possibility of designing steeper side slopes than could be safely constructed if clay materials were used for the liner and/or cap systems.

A good example of a geosynthetic cost benefit analysis considering the potential savings from both material replacement and side slope improvement is reported by Purdy and Shedden, 2008. In that project, a 127 hectare landfill, clay liners were used for containment in the previous modular containment cell. In a new cell, a geosynthetic clay liner (GCL) was used to replace a compacted clay liner for internal cut slopes allowing the slopes to be increased from 3H:1V to 2H:1V. There was also a side benefit from the steeper slope excavation in that the sand type excavated material had a market value of $\$4.90/m^3$. A textured HDPE geomembrane was used to replace a clay liner for the final refuse cover and the improved stability allowed the use of steeper 3H:1V refuse slopes as opposed to the original 4H:1V design. They also revised other drainage features as discussed in their paper that led to additional savings (not reviewed herein). The replacement of the clay liner along with the increase in volume and airspace from the modified containment slopes resulted in an estimated savings of $894,516. Significant but relatively minor compared to the increase in capacity gained by increasing the final slope of the refuse from 4H:1V to 3H:1V, resulting in a capacity gain of 5.9 million m^3, which at a rate of $\$19.62/m^3$ for waste disposal would lead to additional revenues of approximately $115 million over the life of the project.

Additional long-term cost savings in retention basins and covers is related to preserving resources (e.g., water) over time. For example, Sadlier, 2013 provides an excellent economic review of using floating covers for evaporation control. He cites a project location with negligible rainfall at 200 mm per annum and an evaporation rate of 100 mm per annum, typical of desert environments in North and South America, Africa, Australia and China as the basis of his analysis. He shows that 50% more storage and 50% more pumping capacity would be required to overcome the evaporation losses in a 150 m long and 100 m wide reservoir in order to maintain a storage capacity of 44 million liters, assuming a water source within 5 km. By installing a floating cover over the reservoir at a cost of $306,000 to mitigate the high evaporation rate, a capital cost savings of $654,000 is obtained by only considering the decreased volume and pumping requirements (i.e., decrease in cost of pipe size and number of pumps) required for the reservoir. This does not include the additional savings from lower operations and energy costs over the life of the project for the reduced pumping requirements and smaller reservoir.

4.6 *Geosynthetics in Reinforced Soil Walls and Slopes*

GRS walls and RSS have not had a history of use that exceeds the performance periods normally associated with these types of structures, therefore other than initial cost savings, as discussed in section 2.2 and 3.4, the lifecycle cost benefit has not been validated for most structures. However, several performance advantages have been documented where environmental conditions are detrimental to the durability of conventional reinforced concrete (e.g., cantilever walls) and/or steel (e.g., in bin walls, sheetpile walls, or soil reinforced walls) and the durability of geosynthetics is not an issue. The primary issue is corrosive environments that would cause premature failure of the steel components including coastal applications, application of deicing salts, and/or where locally available soils contain salts. In these applications significant increase in cost can be associated with improving the longevity of structures relying on steel and/or concrete for support (e.g., impervious concrete and/or protective concrete coatings, use of liner systems over the wall to prevent salt intrusion, or importing structural fill with high soil resistivity). Other factors that affect the longevity of concrete including freeze thaw, sulfate attach, and/or differential settlement requiring appropriate cementitious materials and mix designs for the environmental conditions or, in the absence of which, a significant increase in the long term maintenance costs. The additional cost for improving the longevity and maintenance should then be considered in the development of the apparent long-term cost benefit of using a GRS or RSS.

Another significant cost factor for concrete abutments supported on deep foundations is the maintenance cost associated with the bump at the end of the bridge that occurs due to deferential settlement between the roadway embankment and bridge support. The use of GRS for the support has been found to mitigate this problem. A significant maintenance is created by the bump requiring continuous leveling of the approach slab and, in many cases, replacement over the life of the bridge. In addition, the bump generates an amplification of live load on the superstructure, creating fatigue on bridge elements. On the average, 25 percent of all bridges in the USA are affected by the bump problem and the maintenance cost alone has been estimated at 100 million dollars per year in 1997 (Ha et al., 2002). Over the past 10 years, the US FHWA has been monitoring a number of bridges using GRS-IBS systems along with similar bridges supported on deep foundations and found that the suppression of the bump had been maintained for all in-service GRS-IBS bridges. The first bridge constructed with the IBS method, Bowman Road Bridge, has been in service since 2005 without the development of a crack in the asphalt layer from the road to the bridge (Adams et al., 2011).

As indicated in the introduction of this section, a significant performance advantage of geosynthetics is that they are manufactured, thus the variability can be controlled and the properties are inherently more reliable than soil properties. As a result, the use of a geosynthetic in most cases can reduce the risk of failure (i.e., the influence of adding a material with low variability to a material with high variability reduces the uncertainty of the end result). This improved reliability can be quantified and used to evaluate the improved long-term performance of a GRS or RSS structure.

For example, Cheng and Christopher, 1991 evaluated the reliability of using a 1H:1V RSS versus a 3H:1V unreinforced soil slope, both designed to a factor of safety of 1.3. Using reinforcement in a slope was found to improve the reliability of factor of safety from 16.3% for the unreinforced case to 10.6% for the reinforced case, essentially reducing the probability of failure by a factor of almost 10. This can be expressed as an economic benefit by comparing the cost required to improve the reliability of the unreinforced slope to that of the reinforced slope (e.g., cost of constructing an even flatter unreinforced slope or importing higher quality materials). Alternatively, the cost of the consequences of failure can be assessed and multiplied by the reduction on the probability of occurrence afforded by using the reinforced soil structure (e.g., see Marr, 2007) (e.g., similar to the calculations used to determine the cost of insurance.

The long-term benefits of GRS and RSS discussed in this section do not include the additional savings by using the more sustainable geosynthetic solution (as reviewed in the next section).

5 IMPROVED SUSTAINABILITY

With the growing emphasis on sustainability within the construction industry it is an opportune time to demonstrate how systems using geosynthetics often have a reduced carbon footprint when compared to other traditional geotechnical engineering alternatives. As reviewed in Section 2, geosynthetics often replace larger volumes of materials, which would result in more energy required for production of these materials and the associated transport to the project. Often lower quality soils can be used reducing disposal of waste materials. Even though geosynthetics have similar high embodied carbon and energy similar to that of concrete and steel, the volume is relatively small in comparison (e.g., for construction of GRS walls as compared to concrete and/or steel in retaining walls), resulting in a considerably (and sometimes dramatically) smaller carbon footprint (Corney et al., 2009). There may also be socio-economic benefits with systems constructed with geosynthetics stemming from the reduction in material transport costs and corresponding reductions in congestion, noise and air pollution as well as the wide range of aesthetic options (e.g., green-faced walls and slopes) (Corney et al., 2009).

Three excellent references are available that review the sustainability of geosynthetic applications in comparison to other traditional geotechnical methods, including Corney et al., 2009, Heerten, 2009, and Jones and Dixon, 2011). All three provide an assessment of the impact of geosynthetics on sustainable design and construction.

As an example, the following case studies in Table 7 from the Waste and Resources Action Program (WRAP) (Corney et al., 2009) demonstrate both the cost benefit and potential for reducing the carbon footprint by using systems incorporating geosynthetics, as compared to alternate, more traditional design approaches. The results clearly show that geosynthetics can produce substantial environmental as well as cost benefits. As an example, in the first case study in Table 7, where a GRS wall was used to replace a Gabion wall, not only was there a $600,000 cost savings, but the onsite soils could be reused with no waste removal required and only a small amount of cost increase for using lime to improve the fill resulting in a significant (67%) overall embodied CO_2 savings. As indicated by Jones and Dixon (2011) this is typical where geosynthetics allow the reuse of locally available sustainable resources (LASR, as coined by Samtani and Nowatzke, 2014) and the geosynthetic material required much less energy to produce and transport than the steal used for the gabion structural components, resulting in an overall embodied CO_2

savings of 87%. As indicated in the WRAP report, to develop an assessment of the environmental benefits, a site-by-site, element-by-element approach must be performed considering the construction program, the nature of the geotechnical engineering challenge, the available materials on site and nearby, site supply logistics, and site layout. Guidance is provided in the WRAP report for making assessments for these specific project conditions.

Table 7. Summary of results from Case Studies on the cost and carbon footprint of systems using geosynthetics versus alternate traditional civil engineering systems (after Corney et al., 2009 and Jones and Dixon, 2011).

Project/ Description[1]	Geosynthetic & Alternate Approach	Cost[2] \$1000	CO_2 Savings (tonnes)			
			Waste Removal	Imported Fill	Structure	Total
Environmental Bund	GRS	25	0	14.2	3.2	19.2
	Gabion Wall	629	7.9	43.5	89.2	143
Road Embankment	Reinforced Embankment	633	18.8	263	32.1	314
	Unreinforced Embankment	1410	45.2	409	0	454
Roadway Widening	Geocomposite Drain	171	0	14.0	29.0	43.0
	Hollow Concrete Block Drain	174	0	0	154	154
Paved Road Reconstruction	Geocomposite Drain & Steel Mesh Reinforcement	NA[4]	--	--	--	--
	> Excavation & Thicker Pavement	NA	>1.2 increase	4 increase	--	5.2
Slope Failure Repair	Reinforced Soil Block with Counterfort Drainage	<Time & cost	--	--	0.2	0.2
	Contiguous Bored Pile Wall	NA	--	--	8.9	8.9

1. Detailed description, cost information and CO_2 calculation method are include in the reference.
2. Includes site preparation, additional fill, import of materials, and fuel costs.
3. Values are indicative and include the total CO_2 and that produced from material transport.
4. NA = Not available

Sustainability of geosynthetics as compared to classical engineering can also be calculated based on the cumulated energy demand (CED) and CO_2 emissions as proposed by Heerten, 2009. The advantage of this approach is the recognition of the high energy content required to produce some products and the complexities to determine the sum of the energy from all resources required to provide the product including the processes involved in its production, delivery and installation, requiring both values to provide a more comprehensive assessment of sustainability. Heerten also recognizes that an even more complete life cycle assessment (LCA) could be performed, which would also include environmental impacts during the utilization phase, as well as removal and disposal of the product, if required.

The results of CED and CO_2 determinations for several projects considering geosynthetic solutions versus traditional practice are shown in Table 8 from Herten, 2009 and Egloffstein et al, 2010. The first project provides comparative CED and CO_2 determinations for a project considering the use of a geogrid reinforced steep vegetated slope with an erosion control mat versus using a vertical, reinforced concrete gravity retaining wall. While the geogrid RSS solution required 40% more soil to be excavated, transported and installed, the CED and CO_2 emissions were found to be about 3.5 times and 5.4 times, respectively, less than those calculated for the reinforced concrete gravity wall. In the second project, subgrade stabilization using geogrid reinforcement found reductions of CED of 81% and CO_2 of 96% as compared to the use of lime stabilization. The third project compared using a GCL with a compacted clay liner for dyke repair and found that using the GCL reduced the CED by about 40% and the CO_2 by about 60%, but, as the reference indicates, the advantage depends entirely on the transport distance of the clay.

6 SUMMARY REMARKS AND CONCLUSIONS

The goal of this paper is to provide detailed cost information for a number of routine geosynthetic applications including clearly identified initial, intermediate and long-term cost savings. Initial cost savings typically ranging from at least covering the as-installed cost of the geosynthetic up to 50% or more of the alternate civil engineering design were identified in applications where the use of geosynthetics resulted in reduction of the quantity or need for select soil materials. In one project, over an order of magnitude

Table 8. Summary of Case Studies on cumulated energy demand (CED) and CO_2 emissions for projects using geosynthetics versus alternate traditional civil engineering systems

Project	Geosynthetic & Alternate Approach	CED GJ	CO_2 tonnes	Reference
New roadway embankment near Frankfurt, Germany	RSS	1350	101	Heerten, 2009
	Reinforced Concrete Wall	4549	542	
District road K34 near Aix-la-Chapelle, Germany	Geogrid Subgrade Stabilization	1182	49	Heerten, 2009
	Lime Subgrade Stabilization	6383	1325	
External Sealing of Kinzig River Dyke, Germany	GCL	2585	145	Egloffstein et al, 2010
	Compacted Clay Liner	4403	357	

cost savings was identified where the geosynthetic allowed for the use of less select on site materials versus the alternate design approach, which required importing more competent structural materials, including fill material, concrete and steel. Similar savings were identified in applications where use of geosynthetics allowed for easier and/or accelerated construction. Of course, in some applications, the geosynthetic is an added cost not covered by the initial cost savings and thus its use must be justified through improved performance. In applications where geosynthetics have clearly been identified as improving long-term performance, the range of potential saving was equally substantial to that identified for the initial cost savings, ranging from a 5% improvement in design life to well over 100%, returning many times the investment in terms of the cost of the geosynthetic. Again, in one case where geosynthetics were used to extend the life of a containment system, the identified potential cost savings were two orders of magnitude greater than the initial construction costs. Finally, and for the future, based on the carbon footprint of the applications reviewed in this paper, the opportunity using geosynthetics as a method for improving sustainability is significant. This ecological benefit is typically in addition to the other cost savings identified in this paper, and will inevitable have a significant impact on the use of geosynthetics in the future. Each application should be individually evaluated for specific project conditions following the methods outline in the references in Section 5.

There are of course many other applications that are not covered in this paper due to the breadth of geosynthetic materials and applications; however, many of the applications were not included due to the absence of quantitative documentation of cost savings, especially over the life of the application. This is especially the case for new products and new applications, even though there may be an apparent significant potential for future savings. Recognition of a few of those innovations is an appropriate ending to this paper. One of the more exciting advances is the development of smart (instrumented) geosynthetics (e.g., geosynthetics with fiber optics strain sensors and moisture sensors imbedded during the manufacturing process and products with embedded sensors for leak detection), which can readily be used to monitor the performance of the geosynthetic. These geosynthetics have the significant potential for cost savings through risk mitigation, especially for evaluating new design methods, alternate materials and immerging accelerated construction methods as well as provide a method for detection of geotechnical hazards.

There are also ongoing efforts to optimize geosynthetics in design for improved performance, accelerated construction, and improved sustainability (e.g., the GRS-IBS systems where the design synergistically combines geosynthetics with other structural elements). Another good example of optimizing design is the use of geosynthetic reinforcement in combination with steel mesh secondary reinforcement to allow for wider spaced primary reinforcement, while maintaining local face stability (e.g., Di Pietro, 2002).

Geocomposites were only covered to a limited extent in this paper, partly due to the young life of these materials. Their economic benefit is predictable in terms of long term performance (e.g., geocomposites for pavement overlays), extending the use of less select geotechnical materials (e.g., horizontal drainage in pavement systems), and accelerated construction (e.g., geocomposites for subgrade stabilization). In terms of sustainability, there are also significant advances already being achieved in using geosynthetics to facilitate construction with recycled materials. Finally there is a significant potential for economic advances in automated geosynthetic installations (e.g. in the construction train for cold in-place pavement recycling and trench drain installation where pipe, gravel and geosynthetic are simultaneously placed).

On a final note, there is a significant need for cost information to be compiled and readily accessible to owners and engineers who make decisions on the use of geosynthetics. At least in the US, there is often misleading cost information provided by opposing industries that are negatively affected by the use of geosynthetics. To address this issue, the author would like to propose that an international registry of life cycle cost information for geosynthetics be assembled and maintained (e.g., by IGS). Hopefully this paper will provide the impetus and basis for that effort.

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