Adoption and implementation of GRS design concepts A consultant's perspective

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ABSTRACT The design and construction of retaining walls is an important aspect of geotechnical engineering practice in the development and maintenance of the world's civil infrastructure. A broad variety of design and construction methods are currently available to designers and contractors. Guidelines and standards exist for most of the design methods currently employed around the world. However, geotextile[1] reinforced soil composite (GRSC) walls, which use ancient, robust and proven design and construction techniques, are currently not covered by any widely known or accepted design and construction guideline or standard. When referring to this type of design as GRS, some professionals, researchers and government agencies consider it to be a simple subset of the widely accepted mechanically stabilized earth (MSE) design and construction technique. However, there are many fundamental engineering differences between MSE and GRSC including recognition of: compaction-induced stresses (CIS); geotextile-soil interaction; reinforcement spacing versus aggregate particle size; stresses and strains in the reinforcement; creep behaviour; and quality assurance / quality control (QA/QC). Full-scale test comparisons of MSE and GRSC walls have demonstrated the fundamental design and performance differences between these two technologies. When using an MSE design approach for GRSC walls, the beneficial effects of the geotextile can be underestimated and the soil loading imposed on the geotextile can be overestimated. The use of MSE design standards for GRSC walls is not supported by the current state of knowledge of soil-geotextile composite behaviour. In addition, the MSE design standards encourage the use of wide spacing between reinforcement layers. This financially favours the use of strong, uniaxial grid type reinforcement; increases the complexity of the designs; and increases the difficulty of project QA/QC. In other words, MSE wall design standards do not support or acknowledge composite behaviour and as such their application to GRSC wall design is fundamentally unsound. A simple, independent standard for GRSC wall design and construction is required to encourage the re-emergence of this economical, robust and proven technology.

Introduction

The use of reinforcement in the construction of man-made earth structures such as walls and embankments is an ancient construction technique likely dating back some 6000 to 7000 years (Jones, 2002). The most widely recognized reinforced soil technology is the Adobe form of house construction which utilizes a mixture of sand, clay and straw to form bricks. This differs from the "rammed earth" or "beaten clay" approach to building walls which does not include tensile reinforcement. In the absence of clay materials to bind the soil, alternative construction techniques evolved out of necessity. Notable evidence of ancient reinforced structures include: the portion of the Great Wall of China constructed through the Gobi Desert; and the Agar-Quf Ziggurat located approximately 5 km west of modern day Baghdad, Iraq.

According to Jones (1985) the older of these two structures, the 3150 year old Agar-Quf Ziggurat, was constructed with a 130 to 400 mm thick clay-fired brick face, layers of woven reeds vertically spaced at 0.5 to 2 m and compacted sand and gravel. Based on visual observations of the Gobi Desert portion of the Great Wall of China, the wall was constructed with a moving form, layers of willow and grasses spaced at 0.2 to 0.3 m and compacted gravelly sand.

Jones (1985 and 2002) reports a number of other historic applications of reinforced soil technology dating up to the early 1900s. For some reason, possibly the invention of cement in the early 1800s, the use of this form of construction virtually disappeared from the construction scene in modern day Europe and North America until the mid 1960s when French Architect Henri Vidal attached steel strips to the back of concrete wall panels to presumably reduce soil loading on the concrete (Holtz, 2004). This quasi-reinforced soil structure is known today by the trade name of Reinforced Earth®. It is worth noting that other than the use of steel and concrete, this approach is basically the same as both log and timber crib construction techniques which have been used for centuries.

Approximately the same time that the reinforced earth concept was being developed, engineers in

[1] The term geotextile refers to the use of textiles in geotechnical applications. J.P. Giroud has been credited for the development of the term geotextile.

both Europe and the United States were experimenting with the concept of reinforcing soil with layers of textiles (Holtz, 2004). These two developments appear to have been the first steps in the direction of rediscovering the ancient art of reinforcing soil.

Although it has been over 40 years since the first modern day version of reinforcing soil began, the road to rediscovery and understanding of soil reinforcement has not been smooth. Government, academia and industry have all played an important role in developing and understanding reinforced soil. The result of this vast volume of global research, testing, application and monitoring is the emergence of two distinctively different technologies. Stabilized earth, also known as mechanically stabilized earth or MSE and geotextile reinforced soil composites or, for the purpose of this paper, GRSC. For many years research into the behaviour of reinforced soil structures have used the term MSE as a broad term intended to capture structures reinforced with either metal or geosynthetics such as geotextiles or geogrid. In doing so, the term geosynthetic reinforced soil or GRS has been considered to be a simple subset of MSE. Examples of the somewhat interchangeable use of the terms can be seen throughout the technical literature in the titles of technical papers such as Elton et al. (2004) "Mechanically Stabilized Earth (MSE) Reinforcement Tensile Strength from Tests of Geotextile-Reinforced Soil [GRS]."

Over the past fifteen years or so, extensive work on the effects of spacing on the performance of geotextile reinforced soil structures has been done. This work has led a number of researchers to adopt a more restrictive definition of the term GRS to include a sufficient limitation on reinforcement spacing that would impart composite behaviour on the resulting structure. The result of this is two fundamentally different technical definitions of GRS.

The research into composite behaviour has given rise to government funded attempts to change MSE design standards to reflect the fundamental, practical and technically uncontested differences between the two technologies (Wu, 2001). However, to date, all attempts to change the MSE design standards to reflect the differences in technologies have been unsuccessful.

There are several possible reasons which may be speculated for the failure of the proponents of the GRSC technology to impart change in the MSE design standards despite the overwhelming evidence. One may be the long-standing interchangeable use of the two terms in technical papers. A second could be the current two definitions of GRS. A third would require a broader look at the role and evolution of technology in civilization. In his discussion on the ancient difference in rates of development of innovations and spread of technology, Diamond (1999) claims that the diffusion of "*technology takes place in the absence of formidable barriers*" and connectedness or unification is a disadvantage as "*a decision by one despot*" can "*halt innovation*". In contrast independence results in multiple "*completing statelets and centres of innovation. If one state did not pursue some particular innovation, another did, forcing neighbouring states to do likewise or else be conquered or left behind economically.*"

Over the past century, possibly due to globalization, there has been an increase in the number of standards which impact almost all aspects of society from product strength, size, speed and durability to manufacturing processes, design, labelling and workplace procedures and safety. These standards exist at all levels of our society, from corporate to state, country and global. Where one state or country does not have a standard, it is not uncommon for it to adopt the standard of another country or organization.

Given the world-wide magnitude and importance of the retaining walls in our civil infrastructure, it is not a surprise that standards for the design and construction of walls exist at many levels. As with many standards, there are always competing interests and material manufacturers and suppliers have played, and continue to play, key roles in the formulation of both the manufacturing standards for the component parts and the design standards for the walls and embankment slopes.

Many block and reinforcement suppliers provide "free" design services and/or free software for the design of MSE structures. These services and products are provided assuming the manufacturer's product would be either specified or favoured for the project. Unfortunately this approach places a disproportionate amount of control over the science in the hands of special interest groups.

Based on recent history, rapid growth in standards and the observations by Diamond (1999), one could conclude that standards are a form of unification and as such become a formidable barrier to innovation and the spread of technology.

In most areas of the world, engineering is defined as the "application of science". In more detail, it can be thought of as the practical application of science to the development of efficient and economic systems, processes, products and procedures to the benefit of society. The engineering profession thus requires knowledge of science and application of professional judgment to further innovation. Innovations evolve into technologies which can be adopted and applied by other professions such as technologists.

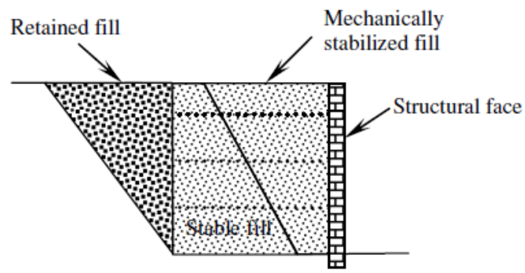
When engineers become aware of a substantial body of scientific evidence which demonstrates there are more efficient and economic means to design and construct a product, engineers should be able to exercise professional judgment in the pursuit of these new design and construction techniques. However, this can become a challenging task when: contractually bound by standards which may be incorrectly applied or interpreted in a manner that discourages the use of the new design and construction techniques; or if no design and construction standards currently exist for the new technology. This underscores the current situation with the application of GRSC wall design and construction techniques.

Stabilizing earth or constructing composites

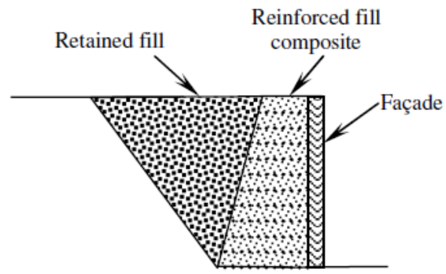
Mechanically stabilized earth (MSE) is analyzed, designed and constructed in the same manner as a tied-back wall. The soil component is considered as one large soil mass with a given density and friction angle. The stabilization is designed with a given strength and spacing to resist the theoretical loading which would have been imposed by the non-stabilized soil. A facing unit is also provided to resist the loading imposed by the soil between the embedded tensile elements and assumes a linear increase in loading as a function of the wall height. The reinforcement is secured to the facing units to hold the facing in place. The combination of reinforcement, facing and connection detail typically form a proprietary design system which is engineered to work together. The influence of the soil reinforcement on the internal shearing within the soil mass is ignored.

GRSC treats the soil and the reinforcement in a composite manner wherein the geotextile reinforcement is placed at a sufficiently tight spacing as to influence the fundamental particle-to-particle interaction of the soil. In other words, the tight reinforcement spacing imparts an elevated confining stress on the soil. This is similar to the confining effect cement has on soil particles in a well-designed and constructed concrete. With the exception that the confinement in a concrete is internally bound at the void space level compared to what could be called external confinement within the GRSC. The facing units within the GRSC are purely a construction aid and a façade for the wall face. As the facing only needs to resist construction-induced compaction loads, the potential material types, shapes and geometries of the facing are only limited by the availability of materials, the economics of the project and the imagination of the designer. Geotextile reinforcement may be selected from a number of different suppliers based on economics and availability.

Fig. 1. Basic difference between a) MSE and b) GRSC wall designs (modified from Giroud, 1980).



a) Tied-back *"Connected to"* Technique



b) Reinforced *"Placed in"* Technique

Figure 1 illustrates this fundamental difference between MSE and GRSC as introduced by Giroud (1980). In defining the different applications of geotextiles Giroud draws a distinction between a tied-back approach to design in which *"the geotextile is attached to two earth, rock or concrete masses which have a tendency to move apart; its function is to keep them together."* This is in contrast to his definition of reinforcement where: *"the geotextile is placed in a soil which is not able to withstand tensile loads applied on it; its function is to carry the tensile loads."*

Evidence of ancient Chinese wall construction techniques indicates that the walls were built using a reinforced soil-composite technique and a movable, leap-frog form with the fill lift thickness limited to what could be effectively compacted by hand-tamping. The section of the Great Wall of China constructed through the Gobi Desert approximately 2200 years ago may be the earliest know relic of a reinforced soil-composite wall.

Design Standards

Applicability

The current design standards for MSE walls uses a tied-back approach to the design of the geosynthetics. This is the same as the "*attached to*" approach referred to by Giroud (1980).

Wu (2001) working under contract for the Colorado Department of Transport, synthesized a large volume of available research, testing, construction and monitoring information on MSE and GRSC design technologies and prepared a report entitled "Revising the ASSHTO guideline for the design and construction of GRS walls". The report identified key features of GRSC behaviour which were realized as a result of tight spacing between reinforcement layers. These features included: significant reduction in lateral earth pressures on wall facing units, lower tensile loading on the reinforcement; a relative absence of long-term creep in the reinforcement when using granular fills; opportunity to shorten the base level reinforcement layers (truncated-base walls); and the potential to eliminate wall embedment. This information was presented to the American Association of State Highway and Transportation Officials (AASHTO), and despite the still uncontested conclusions, was not incorporated in the 2002 revised AASHTO standards for MSE wall design.

Also in 2001 Leschinsky and Vulova published the findings of the FHWA and Delaware DOT sponsored 2000 Master's thesis work of Vulova. The paper entitled "Effects of geosynthetic spacing on failure mechanisms in MSE block walls" used finite element analysis to model the influence of reinforcement spacing on global and internal wall failure mechanisms. The paper concluded that external stability factors governed wall failure with tight spacing of the reinforcement. This contrasted with internal and compound failures governing stability with wide spacing of reinforcements which is typical of current MSE wall designs. In addition, the paper concluded that the findings could result in substantial reductions in reinforcement length requirements to as much as 30 to 40 percent of the wall height by virtue of the elimination of internal failure potential. The findings also state that "*AASHTO disregards the effects of reinforcement spacing and thus, considers that an external wedge always develops internally.*" The complete study was published in 2003. These findings are consistent with those of Wu.

In 2007 the ASCE GeoDenver conference hosted a two-day stream of talks aimed at the identification of deficiencies in MSE wall design. Papers presented by Wu (2007a and b), Adams (2007 a and b), and Barrett and Ruckman (2007) included: "Lateral earth pressures against the facing of segmental GRS walls"; "Myth and fact on long-term creep of GRS structures"; "Mini pier experiments Geosynthetic reinforcement spacing and strength as related to performance"; "GRS a new era in reinforced soil technology"; and "Geosynthetic reinforced soil integrated abutments at the Bowman Road Bridge in Defiance County, Ohio". These papers coupled with earlier work by Wu, Leschinsky and Vulova highlight the importance of tight fabric spacing in forming a composite.

Presented at the same conference was a paper by Collin et al. (2007) entitled: "State-of-the-practice design of segmental retaining walls: NCMA's third edition manual." The paper highlighted a number of changes to the National Concrete and Masonry Association (NCMA) 2006 Third Edition Design Manual for Segmental Retaining Walls (DMSRW). Most of the changes revolved around the wall facing. Of note is the consideration of face-bulging and the change to a "*more rigorous compound stability analysis*" to design the wall face. With respect to the design of internal stability, the paper stated that "*particular emphasis on the use of the compound stability analysis to improve the efficiency of the internal stability design.*" The paper makes no reference to the extensive work on the benefits of tight reinforcement spacing on the stability of reinforced soil structures or the potential to eliminate internal stability concerns by reducing the reinforcement spacing particularly in the wall face area. In fact, the term "spacing" is only used three times in the entire paper.

Bathurst et al. (2006) published a paper entitled: "The influence of facing stiffness on the performance of two geosynthetic reinforced soil retaining walls." The paper concluded that using 0.6 m spacing on the geosynthetic reinforcement, a flexible, wrapped-faced retaining wall, would experience greater tensile stress in the reinforcement than a rigid-faced wall. These higher fabric stresses, reported to be 3.5 times greater than with the rigid face block wall, typically attenuated to the same as the block wall beyond about 1.5 m of the wall face. The technical aspects of the paper and the conclusions were debated by Leschinsky (2007) and the fundamental conclusions were contested by Barrett (2007b). However, the actual test results appear to be reasonable as one would typically expect the stiff wall face to provide greater support for the unrestrained soil between the reinforcement layers. This support would reduce the support required by the geosynthetic layers. When the stiff MSE wall face element is removed, the soil loads are transferred to the reinforcement. In this case, with the wide spacing of 0.6 m between the reinforcement layers, soil loads in the range of 3 kN/m^2 would be expected (Wu, 2007a). The end of construction tension in the geosynthethic measured in the experiment was approximately 2.2 kN/m. This is close to the 1.8 kN which would have been predicted using formulae proposed by Wu, which would not have provided adjustments for increased loading caused by slumping of fill into the geosynthetic wrap following construction. Despite the technical nature of the debate created by the subject paper, Bathurst et al. conclude their reply to the discussion with the following statement:

"The authors agree that using a large number of reinforcement layers (e.g., smaller spacing at 200 mm) results in attenuation of reinforcement loads at the [face] *connections. However, as mentioned in the response to the previous discusser, this is usually not an economical solution. It is more efficient to keep the reinforcement spacing at a large a spacing as possible (e.g., 600 mm in our case) to be compliant with ASSHTO and NCMA recommendations and use the stack of facing units to carry a portion of the earth pressure. However, we agree that encouraging smaller reinforcement spacing to improve redundancy in the reinforced system and reduce reinforcement loads is desirable, provided the structure is economical."*

Key components of this quote are the promotion of wide spacing by ASSHTO and NCMA and the recognition that tight spacing is a good idea provided it is economical. However, the quote refers to redundancy in reinforcement rather than recognition of composite behaviour created by tight spacing. Much of the dialog that followed the publication of this paper could be explained simply by drawing the distinction between MSE tied-back design and GRSC composite design. However, writers on both sides of the discussion were both using the term GRS but undoubtedly were using two different definitions.

Reinforcement spacing

The current MSE design standards for stabilized earth walls utilize an active earth pressure approach and a Rankine failure wedge to analyze the soil mass and subsequently select an appropriate strength and spacing of the stabilizing layers. The approach assumes a linear relationship between tensile reinforcement and spacing as shown by equation [1]. Based on this simple assumption, designers may optimize their designs varying one or more of the following: the spacing between reinforcement layers; the strength of the reinforcement; and the percent coverage of the reinforcement.

[1] $T = S_v \sigma_h$

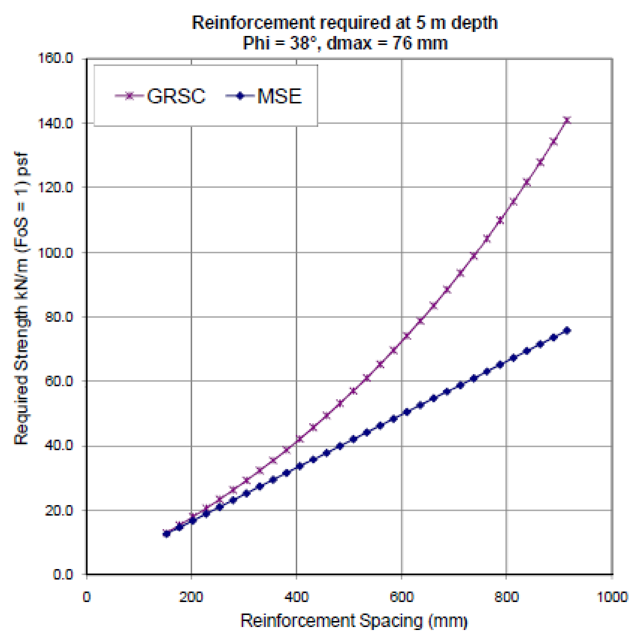
This fundamental design assumption has been proven to be incorrect as cited in Wu, 2001 and Pham, 2009 referring to works done by Adams (1997 and 2007); Elton and Patawaran (2004 and 2005) and Ziegler et al. (2008). These works have demonstrated that spacing plays a far more important role in the engineering properties of a composite soil mass than the reinforcement strength. This engineering principle is fundamental to the design of other composite materials. Pham has proposed the use of equation [2] to calculate the ultimate strength of fabric within a composite structure. Figure 2 illustrates the substantial difference between the linear MSE design approach and the logically non-linear approach of GRS composite design.

[2] $T = \dfrac{S_v \sigma_h}{W}$

where $W = 0.7^{\frac{S_v}{6d_{max}}}$

Based on Figure 2 it would appear that the reinforcement requirements based on current MSE design theory, underestimate the required strength of the reinforcement. However, the potential extent of the non-conservative nature of this estimate would have to consider the fact that one key parameter within the GRSC design approach has only been calibrated and tested with spacing up to 0.4 m. Therefore the level of non-conservativeness may be more than shown. The potential that conventional MSE design approaches underestimate the required tensile strength of the reinforcement was proposed by Claybourn and Wu (1991) where they provided the following quote: *"…the study results indicate there is*

Fig. 2. Comparison of reinforcement requirements at 5 m depth for MSE and GRSC wall designs.



a tendency of the methods to underestimate the amount of reinforcement required for a high wall. This has probably not been a problem due to the safety factors typically used in design and since relatively few walls have been constructed. However, the results demonstrate a general lack of knowledge of high geosynthetic-reinforced soil walls".

Dilation and shear bands

In order to develop a shear plane in a compact or dense granular soil, the soil particles need to dilate so they can move past adjacent particles. If this does not happen, the failure of the soil mass is governed by the strength of the aggregate within the mass. In other words, the mass is as strong as bedrock of the same lithology. Within concrete design, if the cement is sufficiently effective in binding the soil particles, the strength of the concrete approaches that of the aggregate. Within a properly designed and constructed GRSC, the fabric spacing would be sufficiently close such that the fabric resists dilation of the soil particles. This suppression of dilation substantially increases the strength of the composite.

In the early 1970s it was recognized that a design procedure for a GRSC would have to include a reference to aggregate size and fabric spacing (personal communications with J.P. Giroud, 2010). However, there is no such reference to an aggregate size-spacing relationship within the AASHTO or NCMA design standards.

Jones (1985) reporting on work done by Smith (1977) and Jewell (1980) comments on the effect of spacing on reinforcing elements, stating that: "*Below a certain spacing interference occurs, with the consequence that as the spacing reduces the increase in shear strength of the reinforced soil provided by each reinforcement is reduced.*" This observation was based on direct shear testing of round steel bars embedded in sand. The tests showed that beyond two bars, the incremental increase in strength per additional bar decreased and beyond 8 bars there was no further increase in shear strength. This observation is not surprising as the bars are independent and free to rotate within the soil mass. As rotation occurs the bars would work together to dilate the surrounding soil. This reduces the incremental increase in shear strength by additional bars.

Interpreting and extrapolating the steel bar, sand shear box test results to geotextile sheet reinforcement would need to be done with caution. The test suggests a decreasing rate of return between 2 and 8 bars due to interference. As the soil and steel are strain incompatible, shearing across the steel causes the bar to rotate within the soil mass. This rotation causes the surrounding soil to dilate as the bar moves through the soil. The dilation affects the soil within a specific distance of the bar. This is currently referred to as the development of shear bands. As more bars are added, the shear bands begin to overlap. It does not become easier to shear through the composite soil steel mass when more bars are added – it is just that the incremental increase is less and at a point it simply becomes the shear resistance associated with tipping over a stack of steel bars. This interpretation of this test would indicate that the optimum number of steel bar inclusions to restrict soil dilation within a soil-steel composite would be the point where there was no increase in shear resistance of the composite mass due to additional bars.

The concept of shear bands and interface behaviour has been recognized by a number of researchers over the past decade or more [Ketchart and Wu (2001) and Chenggang (2004)]. To study this phenomenon, researchers pull reinforcement out of a soil and measure the effects on the surrounding soil. In this manner, one can deduct that the soil reinforcement would influence the movement of the soil within the same zone. In addition, researchers have been able to model this behaviour in finite element. By decreasing the reinforcement spacing to a set distance as governed by a given particle size within the soil, the zones of influence of the reinforcement on the soil mass can begin to overlap. The soil continues to become stiffer and stronger. It is at this point where one may consider the structure as a composite.

Creep

Within current MSE design standards, creep is a significant design consideration in the use of polymers for reinforcement. However, creep requires the continued or sustained application of load. When granular soils are used in the construction of a composite, the initial, primary creep results in a reduction in load on the reinforcement and, as compacted granular soils are not susceptible to creep deformation, the reinforcement is not reloaded and therefore creep does not occur. This concept was proposed and confirmed by testing done by Ketchart and Wu (2001). In addition, the concept is supported by field strain monitoring of a number of both MSE and GRSC walls.

However, creep is possible within clay soils if the compacted soils are allowed to become wet. In this case, reloading or continuous incremental loading of the reinforcement could occur and could theoretically result in eventual collapse. However, if appropriate design and construction details are employed, clay backfills could be used successfully. Numerous examples exist around the world in the form of structures constructed using the ancient rammed earth or beaten clay construction technique that did not include the use of layered reinforcement.

However, current AASHTO design standards call for high factors of safety to be used to address theoretical creep in reinforcements, particularly geotextiles. These high factors of safety simply increase the cost of materials used in the construction of GRSC walls providing a bias towards the use of stronger reinforcement inserted at the wider spacing dictated by MSE design guidelines.

Stress and strain in reinforcements

Many studies have acknowledged that the working stresses within the reinforcement of constructed walls are apparently lower than predicted using current design methods [Allen et al. (2001), Wu (2001), Elton et al. (2004), Holtz and Lee (2002), Pham (2009)]. The conclusions drawn from these observations differ considerably. Allen et al. have interpreted this data empirically and developed an alternative design approach known as K-stiffness that supports the use of lower strength reinforcement in MSE wall design. Wu has interpreted the data as representing a stress relaxation within the reinforcement in the granular soil mass and proposed a simple adjustment factor to the $T_{ultimate}$ that is based on geosynthetic polymer type, reinforcement spacing and plasticity of the fines within the soil component. Elton et al. used this information in conjunction with large-scale compression testing of GRSC cylinders to develop an alternative analysis approach which uses a strain distribution factor (SDF) based on an empirical model that brackets a scatter plot of normalized reinforcement strain versus normalized depth. Holtz and Lee looked closely at the information from three MSE walls and one GRSC wall and developed an approach to estimate the maximum wall deflection as well as the maximum reinforcement tension and tension distribution based on a composite modulus concept. The approach draws a distinction between three categories of walls: 1) large spacing flexible face; 2) large spacing structural face and small spacing flexible face; and 3) small spacing structural face. The design approach is based on a parametric analysis of a calibrated finite element model and appears simple and logical.

Unfortunately, the referenced walls observed within the various summary studies are a mix of MSE and GRSC structures. Only five of the sixteen walls analyzed would be classified as composite structures based on the fabric spacing. Of these, performance data was only available for four of the walls. Detailed performance data were only available for the 12.5 m Seattle/Reiner wall.

With the exception of Wu (2001) the researchers propose the use of some sort of combined stiffness modulus based on the ratio of the fabric stiffness to spacing plus soil stiffness. However, this assumes a linear relationship between reinforcement stiffness and spacing. The work by Holtz and Lee appears to have accounted for spacing differences with their three categories of walls. However, the linear relationship between stiffness and spacing is just another way of saying that reinforcement strength and spacing are linearly related. As noted previously, extensive GRSC studies over the last fifteen years have provided substantial proof that this notion is not correct.

In 2009 Thang Pham completed a PhD thesis at the University of Colorado in Denver under the direction of Wu. The laboratory component of the work was sponsored by Mike Adams of the FHWA Turner-Fairbanks Highways Research Center. The work entitled “Investigating composite behaviour of geosynthetic-reinforced soil (GRS) mass” provides an in-depth look at the effect of reinforcement spacing, strength, aggregate particle size and compaction on the behaviour of geotextile-soil composites. To date, it is one of the most comprehensive studies into GRSC behaviour and incorporates over 15 years of research from Colorado DOT, University of Colorado Denver and the FHWA. Based on well-instrumented, large-scale, confined compression testing of GRS composites constructed using woven geotextiles, the research provides substantial proof that the relationship between reinforcement strength and spacing is not linear. The work clearly demonstrated the following aspects of the differences between GRSC and MSE:

- GRSC (Sv = 200 mm, Tf = 70 kN/m) is 3.5 stronger and 1.8 times stiffer at 1% strain than unreinforced soil
- MSE (Sv = 400 mm, Tf = 140 kN/m) is only 2.25 times stronger and 1.46 times stiffer at 1% strain than unreinforced soil
- MSE at a spacing of 400 mm doubling the fabric strength from 70 kN/m to 140 kN/m only increased the strength by 35% and the stiffness at 1% strain by 5%.
- For the same fabric strength (Tf = 70 kN/m) reducing the fabric spacing from 400 mm to 200 mm increased the strength by 108% and the stiffness by 32%.

These test results question the utility that a potentially broad combined stiffness design method based predominantly on MSE case histories would have on both MSE and GRSC designs. They also help to explain fundamental issues surrounding research and conflicting opinions regarding composite designs and attempts to change current standards related to reinforced soil structures.

Biaxial versus uniaxial

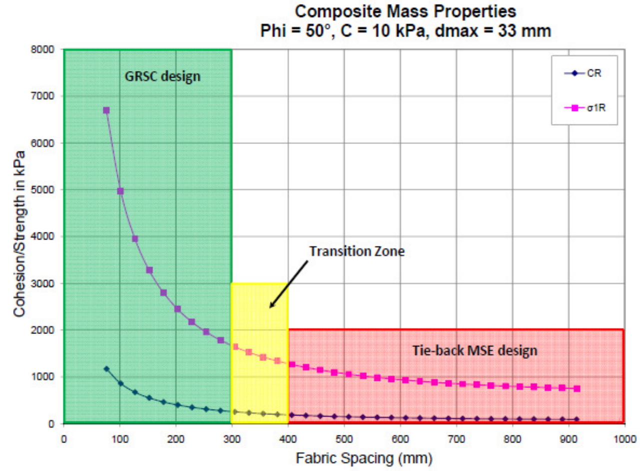
MSE design standards favour the use of geogrids for reinforcement and there is an overwhelming use of uniaxial grids to reinforce soils likely due to their stiffness, strength and availability. The basis for this is likely founded within the modern day evolution of reinforced soil structures starting with two-dimensional basic tie-back analysis and design using steel elements. However, failures of walls are typically isolated to a portion of the wall and as such, would benefit from reinforcement in the longitudinal direction. Providing longitudinal reinforcement in wall design and construction would significantly increase the stability of reinforced soil mass composites.

Design complexity versus simplicity

Within the well-known text "Designing with Geosynthetics" by Koerner (1999) there are sections on designing geotextile and geogrid reinforced walls. The design methodology presented follows a typical tie-back, Rankine failure wedge analysis common to most currently accepted methods. The design examples look to maximize the allowable spacing between reinforcement elements or to minimize the required reinforcement strength in the event that the spacing is fixed based on a particular facing unit. The design process uses a "*trial and error*" approach to compute the reinforcement spacing and is considered to be "*not simple*" and a "*very time-consuming task.*" Koerner also states that: "*In the case of a manufacturer of a particular geotextile style it would be preferred to develop design guides by systematically varying certain parameters in the analysis...*" Possibly in an attempt not to distract designers, within the section on geogrid walls the he states "*many geogrid manufacturers have developed design charts, graphs and computer algorithms for wall designs*" and "*these guides can be considered, since their technical background is usually very good.*" This statement would be clearly attractive to both designers and owners. However, the text does not acknowledge the potential to develop composite behaviour within a geosynthetic reinforced soil mass. The design technique clear follows the *"attached to"* approach and does not address the *"placed in"* approach as presented by Giroud (1980).

By contrast, a GRSC wall design would require consideration of appropriate fabric spacing based on a reasonable thickness of fill that could be economically and effectively compacted considering the available aggregate and compaction equipment. The strength of the reinforcement would be selected based on a required stiffness and ultimate strength of the composite mass. The length of the reinforcement would be based on external and global stability considerations. A design of this type need not be complex. Pham (2009) has proposed equations to calculate the apparent cohesion and compressive strength of a composite mass based on fabric spacing, particle size, friction angle, and fabric strength. These formulae accurately predicted the performance of the large-scale, plane-strain compressive test models used in the study as well as the compressive strength of composites constructed and tested in a number of other studies. Figure 3 provides an illustration of the influence that fabric spacing within a composite design has on the strength of the GRSC.

Fig. 3 Example of the effect reinforcement spacing has on the engineering properties of the GRSC



Compaction-induced stresses

Pham (2009) elaborates on the concept of increase residual lateral stresses within composite structures caused by the compaction processes. The basic concept is that elevated lateral stresses develop within the soil due to compaction. The vertical and lateral stresses are a function of the compaction equipment. When the compactor is removed, the vertical stresses return to normal which is equivalent to the overburden load. However, a portion of the lateral stresses remain locked-in to the soil as a result of the reinforcement layers. These locked-in stresses increase the lateral resistance within the soil mass by providing an apparent increase in confining pressure. Intuitively, it could be deduced that a greater level of locked-in, apparent confinement would be possible by reducing the reinforcement spacing. Conversely, the level of locked-in stresses would be expected to decrease rapidly as the spacing between the reinforcement increased.

Quality assurance and quality control

A key component of any engineering project is the development and applications of quality assurance and quality control (QA/QC) procedures to be followed during construction. As designs increase in complexity these procedures become increasingly critical and ultimately elevate the cost of the project. Alternatively, if the QA/QC intensity does not increase in proportion to the project design complexity, then the risk of project failure increases.

Due to current design procedures and the cost of reinforcement materials, MSE wall designs typically include variations in reinforcement spacing, length, strength and even percent coverage per layer. As wall heights often vary along the wall length, these design variations can become increasingly complex. As such, the potential for construction errors increases. In addition, as reinforcement spacing typically varies, there is opportunity to have inadequate compaction of the backfill as a result of increasing loose fill lift thicknesses to decrease construction time. Large spacing on the reinforcement also represents potential problems in achieving compaction near the wall face in modular block systems where high lateral soil loading combined with compaction-induced lateral loads can displace dry-stacked block units.

Many efforts have been made to address the design and construction issues with MSE walls. These include: the use of clear stone fill near the wall face (a material thought to only require limited effort in order to compact and now incorrectly referred to as a drainage layer); the design of block face units with shear keys, pins or lips; the use of larger and heavier block faces; and the design and use of intermediate reinforcement layers also known as secondary reinforcement or tails. These design and construction details further elevate the level of site monitoring required to provide assurance that the walls are being constructed correctly. A detailed account of problems surrounding QA/QC for MSE walls is provided by Mooney et al. (2008).

The materials required to construct a GRSC wall typically include: a single reinforcement type; a fixed reinforcement spacing that is most often equivalent to a single lift thickness of granular fill usually in the range of 0.15 to 0.3 m; a reinforcement length governed by external and global stability considerations; a single broadly specified backfill requirement that typically includes the terms “compactable” and “granular”; and a simple facing or form system. Construction follows a simple and repetitive three-step process:

1. Install facing
2. Place fabric
3. Place and compact fill

Repeat 1 through 3 to the final wall height. Drainage is installed at either predetermined locations and/or based on actual site conditions and typically involves the use of geosynthetic composites.

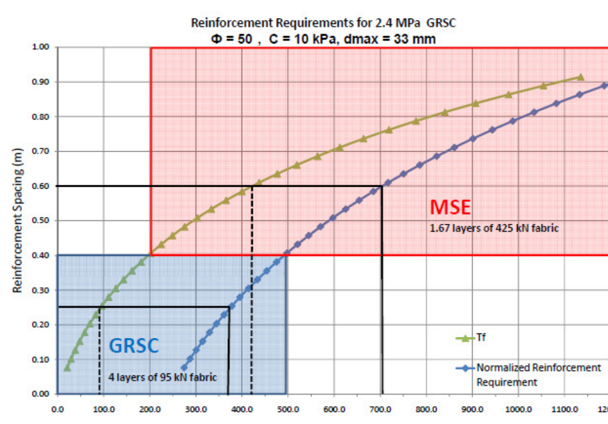
This process requires little contractor training and can be easily monitored. Most geotextiles used in the construction of GRSC are biaxial; therefore they may be installed in either the machine or cross machine directions. Some simple construction rules include: *place fabric on top of every compacted fill layer;* and *only place fill on fabric.* In addition, as the fabrics used for reinforcement are most often affordable, field engineering to enhance the overall global stability of the project can be achieved by expanding the plan area of reinforcement as much as practicable. This gives rise to another simple rule: *if it’s flat make it black.* These rules provide a tremendous advantage with the implementation of a QA/QC program. The repetitive nature of the construction process quickly becomes routine with workers such that mistakes or errors are rare and typically quickly spotted and corrected by the contractor.

Conclusion

A detailed technical discussion on fundamental differences between MSE, tie-back design standards and the GRSC design theory is far beyond what could be practically covered within a short paper. However, the basic difference between designing a restraint to hold back fill material (MSE) or according to Giroud (1980) an *“attached to”* system and utilizing the properties of the fill and construction process to build a composite mass that is internally stable (GRSC) or Giroud’s *“placed in”* system, should be clear. Utilizing the work by Pham (2009) it is possible to calculate the required reinforcement needed to create an internally stable soil mass of a given strength. By fixing the granular fill properties it is possible to calculate reinforcement requirements as a function of reinforcement spacing. Figure 4 provides a summary example of the reinforcing requirements based on fabric spacing as well as the reinforcing requirements normalized to a “per metre” height of wall. From this, it is clear that constructing a GRSC with tight spacing of the reinforcement requires less reinforcement per metre of wall height than the equivalent MSE design utilizing wider spacing. This observation does not include consideration of the potential to reduce the reinforcement length based on Vulova and Leschinsky (2003).

Figures 2 and 3 illustrate the difference between GRSC and MSE design theories. Considering the potentially un-conservative nature of current MSE design methods, it would be beneficial to review the tie-back strength requirements within the current AASHTO and NCMA design guidelines. However, changing this “attached to” standard to reflect composite *“placed in”* behavior would likely create further confusion between the two technologies. Accordingly, it would be more appropriate to develop

Fig. 4 Example of reinforcement requirements based on GRSC behaviour



a separate standard for GRSC design and construction independent of MSE.

The term GRS accurately defines the *"placed in"* concept. However, it has been used extensively in MSE design research and in conjunction with tied-back, *"attached to"* wedge failure analysis. It is therefore important to draw a distinction between GRS research that studies composite behavior and GRS research that is referring to the use of geosynthetics in an *"attached to"* MSE design.

Pursuing a guideline for the design and construction of *"placed in"* GRSC structures is critical to the acknowledgement and adoption of this economic, proven and robust technology. Unfortunately, until a guideline or standard is developed, in some construction environments, the design engineers will need to choose between following the approved MSE standard and adopting GRSC technology that follows sound engineering principles. Adopting this technology can take considerable time and energy to convince owners and approving agencies. Once adopted, cost savings such as those experienced with innovated stream crossings (Adams et al. 2007b, Bradley and VanBuskirk, 2009a, VanBuskirk and Neden, 2007), railway embankments (Strouth, et al. 2009) and resource road retaining walls (Bradley and VanBuskirk, 2009a) could be realized in other sectors.

When looking at the evolution of reinforced soil technology and the issues surrounding MSE and GRSC it is worth while to reflect on Giroud (1980) interesting prediction regarding the future of geotextiles in civil engineering: *"Growing pains are a necessary evil, and history shows that all technologies pass through a disaster stage. The best technologies survive and the disasters serve to strengthen them. With regards to geotextiles, there is nothing to fear; they will stand the test very well, because they meet a need in civil engineering which is too fundamental to disappear."*

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