APPENDIX TWO

Historical Perspectives – The Evolution of GeoMonliths and Unique Composites

INTRODUCTION

Our team at the Colorado Department of Transportation (CDOT) began departures from "traditional" retaining walls in the 1960's under coercion from the U. S. Forest Service. Our structural engineering community had arches, gravity walls and cantilever walls that could be adapted to most situations where space was constrained. There was apparently no demand for expansion of the suite of walls choices.

This paradigm changed when the CDOT applied for a Use Permit to construct I-70 over Vail Pass. The U. S. Forest Service had seen the huge scars visited on the Straight Creek (west) approach to what are now the Eisenhower Tunnels. They demanded that more bridges and retaining walls be incorporated, and moreover, more attention to esthetics. Traditional wall systems were precluded.

Our CDOT team conducted a two-year research and development project to provide a more esthetically appealing wall system. The result was called the Planter Box Wall. We first built a 40-foot high demonstration wall in a gravel pit in Denver and then a 60-foot high wall for I-70 on Vail Pass. One of the overreaching results of this work was the beginning of a paradigm change in what a retaining wall could be. No longer were these features just utilitarian and cookie cutter in design.

That this accomplishment was not celebrated was curious. We wondered why many of the older engineers, our mentors, did not share our enthusiasm. Lack of interest and even disdain at having to "waste money and time" on out-of-the-box efforts were the common reactions. Paradigm fixity.

60 FOOT TALL PLANTER BOX WALL ON VAIL PASS I-70

Paradigm Fixity

I came to better understand paradigm fixity when I realized I was one of those stuck on the flypaper. That happened when the Federal Highway Administration (Jerry DiMaggio in particular) introduced Henri Vidal's reincarnation of soil reinforcing to the U. S. His version was called Reinforced Earth®. They wanted us to incorporate this on the highest profile project in the U. S……Vail Pass I-70.

Talk about counterintuitive! We were to believe that skinny steel strips in soil would equal the performance and longevity of our Planter Box system? The massive concrete and steel elements that made up our Lego®-type component wall system were obviously superior. We had worked so hard in developing our system. Pride of ownership and accomplishment had taken away our adventurous, pioneering initiatives. We were in paradigm fixity!

Breaking Paradigm Fixity

It helps to understand paradigm fixity. If you don't think there is a need for or that GRS/GCS®/GeoMonolith technologies are not superior to many options for retaining walls or abutments, the likely reason is paradigm fixity. All of us seem to want to find a happy place and stay there. I did that when I was a kid with our Planter Box wall. I could not imagine that there were needs we now could not meet. I wanted to just stop the clock.

The compromise with FHWA was to allow alternate bids on the next I-70 project that required a retaining wall. RECO® assured us they could create the Planter Box look. We were sure they could not compete in our world.

Well, you know that answer. The successful low bidder chose the RECO® system, and we built the second wall in the U. S, right behind the Heart O' Hills in California, back when California was the leader in research and development. We went on to build many more. At the same time, my lifelong partner in engineering adventure, Al Ruckman, P. E., and I escaped the chains of paradigm fixity, realizing that all our technologies are dynamic.   A test for paradigm fixity would be to look at your work or teaching that is a couple of years old. If you have not found ways to improve and advance, then you may be the old fuddy duddy the kids laugh about.

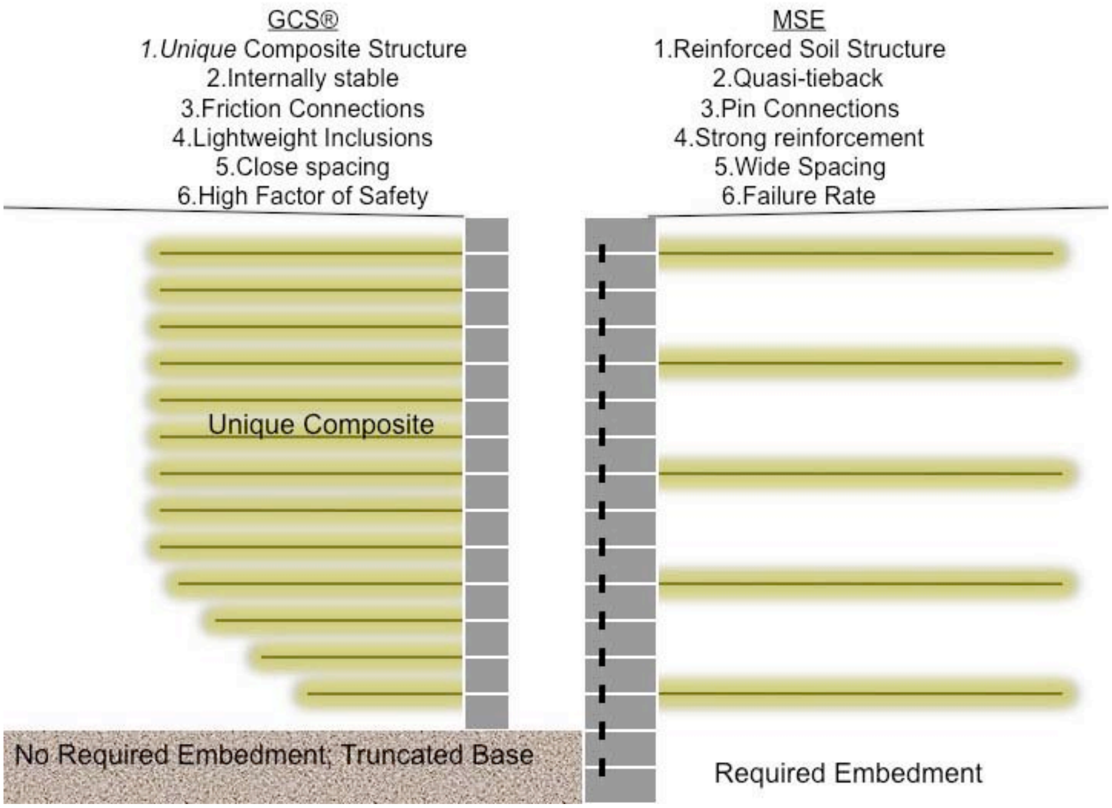
Engineers and instructors are obligated to expand their arts and sciences, and beyond most other professions. Like medicine, standards and practices in engineering materials and methods have far-reaching societal implications and must be continually re-evaluated and advanced.

Credibility

Having joined with the anarchists who demand continual advances in engineering science, Al and I found great rewards in questioning every aspect of our practice. We debunked the notion that swelling soils will not shrink and collapse. We found a climate connection to add to our geotechnical repertoire that is related to the Thornquate Index. We published a paper on Swelling Bedrock and Collapsing Soils, Companion Problems in a Semi Arid climate. We used explosives to mitigate heave in swelling bedrock. We prewet 17 miles of I-70 ahead of construction to mitigate collapsing soils. We investigated dashpots for energy dissipation, which led to patented systems for rockfall protection, most notably the Flex Post Fence. We developed techniques to extend the life of horizontal drains. I chaired an international research project that developed methods and materials with a 2500-year service life to close and seal a geotechnical boring upon its completion. We developed wireline diamond coring bits and techniques for drilling in broken rock…even talus slopes. We patented connections that allow post-construction adjustments for full height concrete facing panels on reinforced soil walls. We developed and eventually trademarked GCS® wall, abutment and rockfall barrier systems that rely on relatively light inclusions on close spacing that elicits interparticle shear in granular soils – and we have participated in thousands of projects that include this technology. We have a patent on what is the very best abutment system for seismic areas known as Earthquake Wings. We invented scour micropiles. We brought the soil nail "cannon" to the U. S. with a successful economic application. We invented SuperNails, a better way to drill in landslide material. We have repaired more landslides than anyone else.

We supported the novel idea of "new" subdivision in engineering that merged soils engineers with engineering geologists, the Geotechnical Engineer. Great idea and continues to provide a needed differentiation from other engineering disciplines; however, the geologist half of this merger was and is poorly represented.

Al and I went beyond government service to work as design/build contractors and founded three specialty companies. Those companies are currently building at least one GCS® wall each week. We chose generic GCS® because it is easier, quicker, less expensive, and less problematic than Mechanically Stabilized Earth (MSE) or ReCo® or any other system we have seen to date. We are primarily capitalists, thus if and when a better system emerges, you bet we will adopt it. We provide warranties on our work and cannot afford the risks with MSE. It is not what a "prudent man" would choose, in our opinion.



COMPARISON BETWEEN GRS/GCS®/GeoMonolith AND MSE

All the braggadocio is presented with humility……Al and I were luckier than most. We lived a charmed life in government service where initiative is tolerated only marginally. We had more than enough research funding. We had great support from our managers. We taught and worked around the world. We collaborated with experts. And we often missed the car pool.

Getting to the point, when we purport to having made a major breakthrough, in this case, defining how to differentiate basic composites from unique composites and therefore correctly visualize confined soil behavior, and therefore develop design protocols, and therefore implement GCS®/GRS technologies appropriately, perhaps we have.

MONOLITHIC BEHAVIOR

A Federal Highway Administration (the progressive ones at TFHRC) project led by Michael Adams demonstrated that a GRS/GCS® composite structure with granular backfill can sustain vertical loading in excess of 20 tons per square foot. This phenomenal behavior is not particularly phenomenal when we compare this to other unique composites. In the process of creating concrete, for example, a small fraction of pozzolanic material confines granular aggregate. Defining unique composite properties is based on testing the composite post-construction.

Geosynthetically Confined Soil (GCS®) is a unique composite that exhibits Monolithic Behavior. Here, granular particles are confined by sheets of woven geotextiles. As we provide a minor fraction of ever closer inclusions in compacted granular soil, properties of the GCS® monolith improve. We can improve those properties to the extent that failure no longer involves just interparticle dilation. We begin to see actual interparticle shear – the same phenomenon we see in high strength concrete – or bedrock. **This is the threshold that defines GeoMonolithic Behavior.**

Defining this exceptional behavior in these terms also provides insight into the wrong turns taken at the inception of design protocols for internally supported systems….MSE being the primary hybridization of reinforced soil theory, or, more simply put, a wrong first step in our search for new ways to build walls and steep slopes. MSE is an extension of Rankine-based failure modes which allow the easy concepts of tiebacks to control. In this paradigm, spacing is not a major factor in performance. Performance is controlled, as in tiebacks, by the strength of the inclusions, by facing connections and stiffness/strength of the facing system.

Design of the GRS/GCS®/GeoMonolith Composite becomes simplistic, even rote with charts. We can test project-specific combinations of inclusions and backfills and determine stress/strain and other properties that may influence site-specific considerations. Just as with a mix design for concrete, we can predict behavior, but have to test full-scale replicas to verify.

That we have taken this long to arrive at this simple explanation is yet another paradox. In the 1970's, researchers and scientists at the U. S. Forest Service and at Oregon State built full-scale structures, the first GeoMonolith composites constructed with geotextiles and granular soil. They described or predicted behavior (think "design") with adapted conventional mathematical formulae such as a Rankine path. There was no questioning, no inquiry, into alternate explanations for internal behavior. Conventional theory seemed to fit the paradigm of conventional wisdom. But it is only close for those simplistic constructions and not close enough to carry forth to more complex structures. **An engineering science and industry evolved that never challenged the founding premises.** And this has caused confusion since.

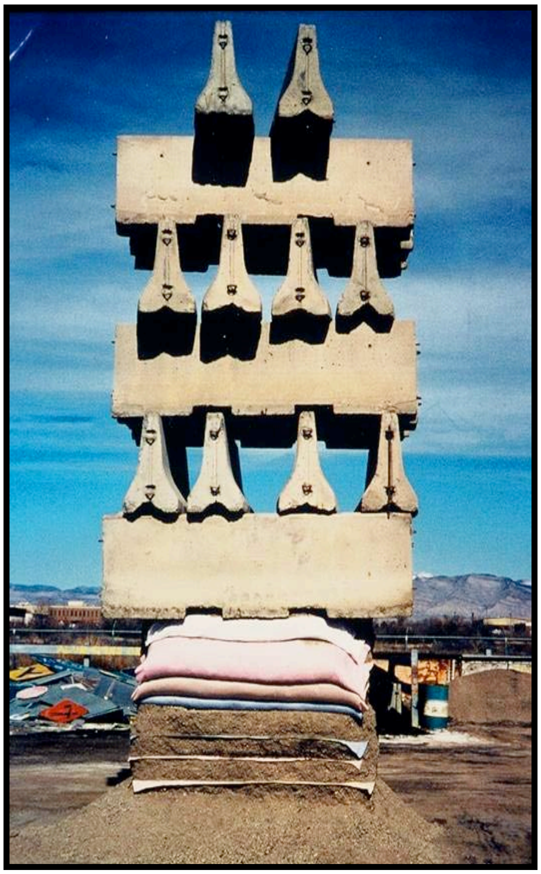
Today, we would not separately quantify properties of cement and those of the aggregate and describe a behavior based on those element contributions. Grout has nominally only a 4000 psi compressive strength, yet we make a concrete monolith – a Unique Composite - with much higher strength. What we do is make a batch, cure it, test it, and those test results become the design properties. Monolithic Behavior. If we need only 50 psi, we reduce the percentage of the confining element, the cement. Or we may use a lesser quality primary aggregate. If we need 5000 psi, we increase the cement content, type and/or aggregate quality. Now we can perform the same iterative process with spacing of the geosynthetic inclusions and properties of the backfill in generic GRS/GCS® GeoMonolith Unique Composites.

A serendipitous result of this approach is that the width of the inclusions is determined by external stability analytical methods. There is no base to height requirement or limitation. We have built GCS® GeoMonoliths 3 feet wide and 30 feet tall. We can truncate the bottom inclusions to avoid excavating competent material- as is sometimes required for MSE. We can build safely with negative batter. It becomes just a solid block in the model……well, except when it is sitting <u>on</u> something, say a soil nail wall, and then we model it as gamma H surcharge. Wouldn't want to get that silly overturning concept from externally supported systems involved.

In contrast, MSE structures built on public projects have a failure rate and are likely to have factors of safety below the designer's expectations as well. And, paradoxically, we see aberrant excursions into "improving" MSE designs, such as statistical concepts like the K something design system that says the geogrids in these failing MSE tieback walls are too strong and too close. And AASHTO is considering just that. A paradox.

Paradoxes. While in-air tests of inclusions are shown not to represent in-soil behavior, particularly in the early loading phases of GRS/GCS®/GeoMonolith Composites, engineers, particularly structural engineers, value in-air stiffness and strength and bias guidelines with those values. This fits with design concepts analogous with tie-back concepts of element contribution. Several of us, including Adams, have demonstrated that close spacing more than compensates for low in-air stress/strain properties. Counter to conventional wisdom of structural engineers, the better structural performance is achieved with close spacing of thin sheets of inclusions than with stiff, strong inclusions on wide spacing.

I demonstrated this in the 1990's with the full-scale bridge pier that used cotton bed sheets for inclusions. Our measured wide strip tensile strength of bedsheets was 12 pounds per inch. I stacked 18 vertical feet of jersey barriers on this pier. Dr. Wu determined we could have stacked a column of these concrete barriers 80 feet high on that **GeoMonolith Unique Composite** that used bed sheets as the confining element. (Cementious element? Bedsheets = cement? How about that for a counterintuitive paradox, or are those redundant terms?)



Bedsheets as Confining Inclusions

WHAT'S IN A NAME?

In the 1980's, I participated in forming Transportation Research Board Task Force 57 on Engineering Fabrics, chaired by Verne McGuffey of NYSDOT. It evolved into a standing committee with a new name – Geosynthetics. Verne arranged for me to become chair (90-97). Our committee labored over this name, knowing that names can influence understanding, acceptance and implementation. We finally arrived to the term, Mechanically Stabilized Earth (MSE). We avoided "reinforced". We wanted to divorce ourselves from the steel strap and bar mat industry and also avoid confusion with capitalized and non-capitalized "reinforced earth walls". We wrote the first design guidelines for MSE, and which was a hasty effort to get this new technology out the door and on the road. Funny how an intelligent, energetic group could all be herded the wrong way.

We continued our research efforts at CDOT, UC/D and at FHWA's Turner Fairbank Highway Research Center. We discovered along the way that some of the precepts included in MSE designs were not correct. We used an array of soil pressure cells to demonstrate that these flexible systems cannot exhibit significant eccentricity. This can also be deduced by using common sense. A concrete footer was counterproductive. We found no reason for mandatory embedment, except to make the walls taller, wider and more expensive. We demonstrated that GRS/GCS® walls have very low facing pressures – due to the close spacing – and that these loads are independent of wall height. I was a conspirator in recommending open graded stone at the face. We wanted to minimize compaction requirements to avoid facing alignment issues. That proved unnecessary; however, this design element was enigmatically preserved as an artifact…and called by the uninformed a "drainage layer". What engineer drains walls at the face? The value is practically nothing and the cost significant.

University of Wisconsin and Ruckman Demonstrations of Absence of Facing Load

We went on to develop alternative facing systems and experiment with novel backfills – crushed glass, tire shreds – anything durable. I called this new system with non-woven geotextile inclusions Mechanically Stabilized Backfill (MSB), to encourage imagination and creativity in expanding this obviously powerful new technology – and to distance ourselves what had become an intractable community stuck in paradigm fixity with MSE.

Later, as our work focused on woven polypropylenes (cheap and durable) inclusions in road base-type backfills (cheap and durable) and ordinary concrete blocks (cheap and durable) as facing, Jonathan Wu at the University of Colorado/Denver and Mike Adams of FHWA decided to use the term Geosynthetically Reinforced Soil (GRS). I later trademarked a name I think is more descriptive, Geosynthetically **Confined** Soil® (GCS®). GRS and GCS® are synonymous, and are further departures from the systems with failure rates, collectively known as MSE.

Just for clarification, I misinterpreted composite behavior and attributed it to tieback concepts at the beginning, as did everyone else. When Al and I discovered our fundamental error, we then recognized the problems with MSE design, but could not create an alternative mechanistic description of what we now call GCS®. Our fellow pioneers did not keep pace with us, and to the extent that many chose to separate from our upward progression and remain entrenched on the easy path of conformity. Just as I did with the Planter Box Wall….we did not want to have to change paradigms yet again.

This has grown to tragicomedy proportions in our universities and within the FHWA. One group of the FHWA actively conducts internationally leading edge research and supports innovative projects while another group openly rejects this research and demonstrations and continues to support MSE instruction and utilization in our state DOTs. Our state and local DOTs and our highway users are victimized by this hiatus.

In keeping with renaming to emphasize some major breakthrough in materials, modeling or design theory, I now use **GeoMonolith** to further differentiate the GRS/GCS® design philosophies from MSE and Reinforced Earth. You may see **GCS® GeoMonolith** or **GCS® GeoMonolith Composite** as well. All of these new names are integral with gaining attention that this is not your father's Oldsmobile.

Another significant effort is ongoing in Canada by Calvin VanBuskirk to separate MSE from true confined soil composites. He has suggested Geosynthetically Reinforced Composite (GRC) or Geosynthetically Reinforced Soil Composite (GRSC) in this redefining process. Mr. VanBuskirk is currently the most innovative engineer in world with his GRSC constructions that include true arches, bridges over soft ground, and walls hanging off impossible cliffs that mock MSE B/H ratios.

Conclusion

GeoMonoliths are difficult to describe in simple mathematical terms. While full scale tests have determined bearing capacity can approach bedrock properties and while a GRS/GCS® GeoMonolith Composite has been demonstrated to be the last structure standing in an earthquake, we cannot yet provide a simple, mechanistic design protocol.

There is easy understanding and a measure of comfort in tieback principles where each element is quantifiable and where behavior prediction (design) is an elementary addition of each contribution, as can be found in tiebacks and soil nails and piling. There is a sense of security in the canned versions of proprietary wall designs that are promulgated by vendors, NCMA and one branch of the FHWA.

Geocomposites, Unique Composites (GeoMonliths) are counterintuitively more analogous to concrete, where the constitutive elements are combined and the resultant product is defined by performance of that amalgam. Development of GeoMolithic Theory has been hampered by wrong turns and sidetracks in evolution, most notably by diversion into quasi-tieback (element contribution design) Mechanically Stabilized Earth (MSE).

MSE can be and will be a standalone hybrid where tieback behavior (design) is extended to a system where inclusions are installed incrementally during construction. Strength and stiffness of the inclusion (reinforcement) coupled with strength of the facing connection and facing stiffness are all components of design, and that design predicts behavior based on the contribution of the various elements.

MSE theory is diametrically opposed to GeoMonolithic Theory. **GCS® GeoMonolith Composites** exhibit unique composite behavior, wherein interparticle shear is the primary failure mode – not rupture or pullout of a tieback - and where performance is best verified by testing of the combination of inclusions and backfills.

Repeating the primary message, **unique composites cannot be accurately modeled using an additive representation of their constituent elements.**

A credible mathematical procedure to predict behavior of variations in components in GCS® GeoMonolith Composites ahead of construction will eventually be developed. However, in this absence, and since we can perform triaxial tests on site specific combinations, there are few legitimate reasons to delay implementation of basic walls, piers, abutments, rockfall barriers, box culverts, sound barriers, arches and more. We have built thousands of "magic" GCS® GeoMonolith Unique Composite structures, and demonstrated they are generally the safest, least expensive, most versatile, quickest and most durable of all systems.

A generic GCS® GeoMonolith Composite is appropriately characterized in design as a block that will not fail internally even with negative batter and that does not exhibit eccentricity. Global stability models are used to determine fabric width. It can be shown as an unbounded surcharge in loading.

Robert K. Barrett
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