Innovative Retaining Structure and Slope Stabilization Technologies

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ABSTRACT

Over the past few decades, several new technologies have evolved into mainstream civil and geotechnical engineering solutions. This paper will provide an overview of emerging technologies that are being implemented to: (1) repair active landslides, (2) repair existing retaining walls and bridge structures without the need for extensive temporary shoring, traffic diversions and other inconveniences, (3) construct massive retaining walls sometimes well over 15 m (50 feet) in height and (4) construct emergency access bridges even in the dead of winter that can sustain massive differential settlement and keep haul roads active even in the harshest environments.

Details regarding the background and recent advancements of the technology as well as nationally recognized design methodologies will be provided. Case studies will be presented that clearly illustrate the potential uses of these technologies in maintaining existing infrastructure.

1.0 INTRODUCTION

Fill slope and earth retention structure failures along impoundments, roads, railways, pipeline, and trails are common and frequently extremely challenging issues. Excavating the failed material out and either replacing it with higher quality soil and construction or new retaining structures are the common or "traditional" methods of mitigation.

These sites repeatedly prove to be technically challenging but are generally underfunded for traditional repair methods. This paper describes recent innovations that have proven to be very efficient in these applications.

Design/build delivery with small inclusions, and lots of them, are the theme of this work. Soil and rock anchors, closely spaced micropiles and geosynthetically reinforced soil (GRS) are the primary tools. Small footprint, few resources, shortened construction timeline and reduced cost with a wide applicability are the typical result.
2.0 DESIGN-BUILD METHODOLOGY

The design/build process creates synergies between the designers and construction crews. The combination of system and process permits real time field alteration as required.

Preliminary design is typically based off basic site measurements, observations, experience and past studies (when available). The assumptions made in the initial design work are verified through the construction process and alterations were made as warranted.

Design methods for the soil anchors, micropiles and GRS generally follow the following publications:

- FHWA0-IF-03-017, “Geotechnical Engineering Circular No.7”

3.0 TECHNOLOGY OVERVIEW

The primary tools used in efficiently repairing shallow embankment failures are soil/rock anchors and geosynthetically reinforced soil (GRS). An overview of the history and application of each of these technologies is provided below.

3.1 Soil Nailing

On Friday, October 21, 1966, after several days of rain, more than 114,683 cubic meter (150,000 cy) of waste spoils from a local coal mine liquefied and surged toward Aberfan, Wales, burying much of the village, including the Pantglas Junior School, in up to 9.1 meter (30 feet) of soil and spoil debris, killing 116 children and 28 adults. Soon afterward, the concept of soil nailing started to emerge in Europe and beyond, and engineers began to investigate how nails could be installed most efficiently. Groups from the UK, Germany, and France independently developed installation methods that included driving, drilling, driving with simultaneous jet grouting, and even chemical explosive actuated firing systems.

Launches Soil Nails

Launched soil nails are a unique remedial technology in the geotechnical construction toolbox. These 6.1 meter (20-ft-long), 3.8 cm (1.5-in).-diameter nails are installed in a single shot using a compressed air “cannon” at velocities of up to 112 meter/second (250 miles/hour), and with installation rates approaching 250 nails/day. The nails reinforce an
unstable or potentially unstable soil mass by transferring the nail’s tensile and shear capacity into the surrounding soil.

The cannon units weigh over 2,722 kg (6,000 lbs) and are typically mounted on a tracked excavator that has been converted to carry a specialized compressor unit rather than a rear counterweight. The units may also be suspended from a crane or mounted on a long-reach excavator for greater range. Initial firings used 3.8 cm (1.5-in.)-diameter, 6.1 m (20-ft)–long, galvanized steel tubes. The tubes can also be perforated to act as drains, or later pressure grouted to improve bond strength, corrosion protection, and capacity. The typical launched soil nail is three-step process:

1. A perforated, galvanized outer tube would be launched to full depth at pressures between 5,515-31,026 kpa (800-4,500 psi)
2. The hollow tube would be pressure grouted with neat cement grout
3. A #6 epoxy-coated inner bar would be inserted before the grout is set.

Fiberglass outer tubes have also been installed in corrosive soil environments, and many projects have been completed where pressure-grouted, launched soil nails were installed in combination with ungrouted, perforated launched drains.

Projects and applications
As of 2016, tens of thousands of launched soil nails and drains have been installed in the U.S., Canada, UK, New Zealand, and Australia. Primary applications have been to stabilize shallow landslides, although the technology has been used to stabilize failing sheet/H-pile walls, for temporary shoring, for pipeline stabilization, and as micropile
foundation support for retaining walls. Launched soil nails have been used in a variety of soil and slope conditions, especially in mountainous areas, where rugged terrain limits construction options. They are primarily fired into sand, silt, clay, and even soils with some cobbles or boulders. Launched nails are not suitable for sites with large/frequent boulders or very hard, shallow bedrock, in very stiff clays, or in areas where failure surfaces exceed 5.2 meter (17-ft deep). Launched soil nails have also been specified on sensitive riparian projects where drill cuttings/grout spoils and excavations often associated with traditional drilled and grouted soil nails would not meet environmental mandates.

Launched nails has proven to provide a fast, cost effective method which can be engineered and designed to provide a 1.3 to 1.5 factor of safety and 75 year design life. Over time, Engineers have become capable of assessing soil conditions related to shallow slope failure mechanisms and have amassed a database and sufficient Engineering knowledge to eliminate the need for extensive site investigations.

**Installation Theory and Corrosion Protection**

The compressed air cannon induces tensile stresses in each tube as it penetrates the ground. This tension counteracts the compressive stresses induced by the displaced soil and thereby prevents nail buckling. The single impulse, high-installation velocity creates a shock wave at the nail tip, which displaces the adjacent soil as the nail penetrates. Nail penetration ceases when accumulated frictional resistance of the soil at the nail tip is sufficient to dissipate the installation energy imparted by the cannon. It’s important to note that during the majority of the nail’s flight into the soil, the main frictional resistance occurs at the nail tip due to the elastic over-deformation of the soil induced by the rapid impulse.
To demonstrate this phenomena, paper stickers were placed on the outside of nails that were launched into a gravel pile, then later carefully exhumed. The stickers remained unabraded even after traveling up to 17 ft into the soil. This phenomena also explains the higher-than-expected bond strengths seen in launched soil nails versus driven soil nails. Not only is the soil displaced by the nail densified (thus creating higher normal stresses along the nail shaft), unlike driven nails, launched soil nails create minimal disturbance to the surrounding soil because of the rapidity of the single impulse. Consequently, launched soil nail unit bond strengths always exceed those of driven nails, and often exceed those of conventional drilled soil nails using open-hole techniques. Launched soil nail bond stresses also tend to increase over time, with studies showing up to 30 percent increases over a 3-year period. Experts theorize that the mechanism for this time-dependent bond strength increase is due to excess pore water dissipation and soil/nail cohesion increase over time.

**Design**

Launched soil nail design methodology is outlined in the joint USFS/FHWA Application Guide for Launched Soil Nails, Volume 1, and relies on the theory that launched soil nails resist soil movement by acting in both tension and shear. In a drilled and grouted nail, by contrast, nail shear contributions are typically ignored. To understand this difference in design assumption, it is important to understand that unlike traditional drilled and grouted soil nails, launched soil nails have a much higher shear capacity to axial capacity ratio. Shear capacities of up to 20 percent or more of axial pullout capacity have been observed in launched soil nails (compared with typical values well below 5 percent for traditional drilled and grouted nails). Because of this difference, the shear component of a launched soil nail is not ignored as it would be in traditional soil nail design using grouted soil nails. It’s important to note that the ultimate shear resistance of the nail is not assumed to be controlled by the shear strength of the nail material, but by the ultimate bearing capacity of the soil in a localized area near the active failure surface. This localized bearing failure develops over a short section of the nail on either side of the failure plane, typically 1 m (3 ft) or less. Typical shear values are also relatively low [generally ranging from 136-544 kg (300-1,200 pounds)].

Although the USFS/FHWA manual provides a detailed discussion of the equations and mechanisms behind launched soil nail capacity, the manual models shallow landslides and embankment failures as a planer sliding wedge, ultimately presenting simplified charts to determine nail spacing for various slopes. These charts, however, do not allow for non-uniform slopes, water tables, or slopes with non-uniform materials. Between 1994 and 2013, if designers wished to model a slope that did not fit neatly into the charts, they were forced to employ a more tedious design method using nail input parameters from the USFS/FHWA manual. In 2013, the computer programmers who developed FHWA’s SNAP (Soil Nail Analysis Program) and SNAP-2 created the free program LSNAP (Launched Soil Nail Analysis Program). This software allows designers to quickly perform calculations that previously required many hours of time. In addition, designs can be
produced using either ASD or LRFD formats, which allows for both static and dynamic loading and highly complex wall configurations.

Launched soil nails have also been mentioned in other federal design documents, and often with increasing accuracy. In the 2003 version of *Geotechnical Engineering Circular (GEC) No. 7 – Soil Nail Walls*, FHWA noted that launched soil nails were “bare bars” that were “only used for temporary nails” and that the method was “not currently used in FHWA projects.” Twelve years and many federally-funded, permanent launched soil nail projects later, the 2015 rewrite of *GEC #7* eliminated the “temporary” restriction and noted that the “technique is applicable to landslide repairs, and to roadway and embankment widening.” While the manual indicates that launched soil nails are generally not grouted, and therefore not actually soil nails, the incidence of launched nails being grouted approaches 90 percent, so perhaps the next version of *GEC #7* will consider launched soil nail technology in more detail. Perhaps the most accurate federal guidance on the technology since the publication of the USFS/FHWA manual in 1994 can be found at [www.geotechtools.org](http://www.geotechtools.org) (see “GeoTech Tools – Your Ground Modification Website” in the November/December 2015 issue of *GEOSTRATA*, pp. 38-42, 44), a website that serves as the culmination of TRB SHRP2 R02 “Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform” program. The project report notes that the advantages of launched soil nails “include rapid construction, easy monitoring and testing, construction with limited headroom and right-of-way, and ability to withstand large deformations.” The GeoTech Tools website contains case studies, cost data, and other useful information on both launched soil nails and myriad other innovative, geotechnical construction technologies.

**New Applications and the Future (2016 and Beyond)**

Because of their speed of installation, technical characteristics, and relative cost compared to drilled soil nails, novel applications for launched soil nails continue to be developed. From foundation supports for solar farms to gas vents for landfills, new non-slope stabilization ideas for the technology may serve to be quite viable in the future. Perhaps the most interesting application developed in the last few years is for permafrost preservation. Engineers in the Yukon are currently investigating whether hollow, launched soil nails can be installed vertically into or around roadways overlying permafrost to stabilize melting northern roads. In the winter, air currents would transmit heat from the soil to the atmosphere, solidly freezing, and therefore stabilizing, the permafrost. In the summer, the currents naturally shut off, preventing convection-based energy transfer. From slope stabilization to natural radiators, there is seemingly no end to the possibilities that innovative engineers may find when utilizing launched soil nail technology.
3.2 Geosynthetically Reinforced Soil (GRS)

Thousands of years before the concept of “Reinforced Soil” became widely accepted, ancient people had already used soil with vegetative tensile inclusions to build structures. As early as 1000 B.C., early Mesopotamians used layers of reeds and packed clay to build the cores of their ziggurats. Portions of the Great Wall in China were reinforced using the twigs of tamarisks trees between layers of gravel and clay. An engineer named Pan in the Ming dynasty was well known for using willows to stabilize earth dikes in China (Barker, 1994). As recently as the 1960’s, tin miners in Malaysia placed grass stems in their mine tailings piles to prevent slope failures (Hengchaovaich, 1999). Adobe and bricks made from straw and clay have been used for thousands of years (and are still used) from the Southwestern United States to Egypt to Central China.

Modern reinforced soil can trace its roots to French architect Henri Vidal in the mid-1960’s. Vidal’s system, known as *Terre Armee* used a dense array of small steel strips to reduce lateral earth pressure in earthen retaining walls. The first Reinforced Earth wall in the United States was built on California State Highway 39 (Northeast of Los Angeles) in 1972. The technology then spread throughout the country. In the mid-1970’s, these structures began replacing reinforced concrete structures previously developed by the Colorado Department of Transportation (CDOT) along interstate 70 near Vail pass. As I-
70 was constructed through Glenwood Canyon, Reinforced Earth walls were also constructed, again using steel as reinforcement (in the form of strips and mesh mats).

Around the same time the U.S. Forest Service in the Pacific Northwest began using geotextiles to enable heavy logging trucks to travel over soft materials (Steward, 1977). In 1974 John Steward of the U.S. Forest Service and Professor Dick Bell of Oregon State University expanded this technology by constructing the first GRS walls in the United States (Holtz, 2004). A 3 m (6-ft) high wrapped-face wall using lightweight geotextile was constructed in Oregon and an 6 m (18-ft) high counterpart was constructed in Washington State. Stewart and Bell analyzed the walls using the tieback-wedge analysis, an adaptation of the work of Professor Lee at UCLA in 1973 (Lee, 1973). This theory was based on the geotextiles acting as “tiebacks” and the soil mass acting as it would on a traditional externally reinforced retaining wall. The equivalent lateral earth pressure coefficient ($K_A$) is determined by assuming a horizontal backslope and no wall friction, given an active zone defined by the Rankine failure plane. The amount of earth pressure at each elevation must be resisted by the geosynthetic “tieback” at that elevation. The “tiebacks” could fail in two modes: pullout and rupture, and the theory analyzed each. The theory was simple and revolutionary, but also over conservative, neglecting any composite behavior of the reinforced soil mass. Although the technology was new, Professor Bell seemed to intuitively understand that close reinforcement spacing would play a key role in wall stability (although Bell was also worried about under compaction, which small spacing helped to prevent).

Once again, CDOT researchers picked up on the revolutionary work with geosynthetics coming out of the northwest. Bob Barrett, Al Ruckman, and J.R. Bell built an 18-ft high wrapped face non-woven geosynthetic demonstration reinforced soil wall on I-70 in Glenwood Canyon, Colorado with onsite granular backfill and closely spaced 20 to 25 cm (8 to 10-in) reinforcement layers (Bell, 1983). Using the models available at the time, portions of the wall had a calculated safety factor of 0.33, but no failure was observed. Massive earth surcharges were added that lowered the safety factor to 0.11, but again the wall remained unaffected. Even after differential settlement of the wall foundation of up to 0.6m (2 feet), the wall was unaffected. Fabric was exhumed periodically to determine degradation in soil.

This research project demonstrated that current models were overly conservative and that internally reinforced structures could endure massive surcharges and differential settlement. For the first time, researchers saw that internally supported structures may be more than a low cost replacement for externally reinforced structures, they may actually be superior. What was not understood at the time was that close spacing was the key to this “better than expected” performance.

The capstone to the GRS research efforts (especially for bridge abutment applications) was a CDOT demonstration project carried out in the Havana Maintenance Yard in 1996 that demonstrated the tremendous loads that GRS systems were able to withstand. Piers as narrow as 2.4m (8 feet) and over 7.3m (24 feet) tall were subjected to 2,340 kN loads
without showing signs of distress during the loading process. Later analysis of the structure demonstrated that these loads were sustained even though the compaction on the piers was sub-optimal [likely due to the difficulty involved in running a plate compactor on an 2.4m (8 foot) wide platform 7.3m (24 feet) above ground] (Abu-Hejleh et. al. 2001).

Later research also demonstrated that GRS with select granular backfill and closely spaced geotextile was one of the most resilient systems to seismic loading (Wu, 2006).

3.2.1 Applications

Following these research efforts, the authors and others in the private sector began using closely spaced, lightweight woven polypropylene geotextile sheets in a well compacted granular backfill matrix in a variety of applications including avalanche and debris-flow barriers, rockfall catchment structures and barriers, retaining walls, and, notably, bridge abutments. All of the case studies presented were completed using design-build contracting on private sector projects. This method of contracting lends itself to the versatile GRS technology. At the time, few bridge engineers were willing to try a “new” technology, so the relatively few design-build firms able to use the technology saw a distinct market advantage over competing firms. Bridges were routinely constructed for less than half what a traditional pile-founded bridge would cost, with construction times often 30% of the traditional option. Today, as more engineers understand the technology most GRS-IBS projects are completed through bid-build contracting, and the technology is much more prevalent in the public sector. Cost and time savings to the ultimate client are similar to design-build contracting once construction commences.
3.2.2 FHWA Design Methodology

Building on CDOT research efforts and the myriad of GRS abutments constructed starting in the late 1990s, FHWA researchers presented an interim implementation manual for Geosynthetic Reinforced Soil Integrated Bridge Systems (GRS-IBS) in early 2011 (Adams, et al., 2011). The manual identified the GRS-IBS technology as simple to design and construct, easy to modify in the field, and appropriate for construction in various weather conditions. The manual also notes that when compared to traditional bridges systems, GRS-IBS costs less (by 25-60%), can be completed in less time, requires less maintenance (primarily by eliminating the “bump at the bridge” due to differential settlement between he abutment and the superstructure) and is more durable (Adams, 2011).

![Figure 5 - Typical Cross Section of GRS-IBS Abutment (Adams et al., 2011).](image)

4.0 CASE STUDIES

The following case studies demonstrate the use of the technologies described above over an array of applications.
4.1  Tied Arch Bridge near Black Hawk, CO (1998)

The abutments were constructed above the city of Black Hawk, Colorado, to support a 118 foot span steel arch bridge. The abutments were constructed with the on-site granular soil and reinforced with layers of a woven geotextile (Amoco 2044) on 30 cm (12 inch) spacing, with native rock as the facing element rather than the more traditional concrete blocks. As with blocks, the reinforcement sheet extended to the front face of the wall to provide a positive frictional connection between the facing and the abutment. Tie rods were drilled through the abutments into bedrock and tensioned to pre-load the abutment prior to bridge installation. Although this method is effective in reducing or eliminating settlement of GRS abutments, later research showed that vertical abutment strain without preloading is well below 0.5% at typical design loads (Adams, 2011).

![Figure 6 - Black Hawk Bridge, with mortarless native stone facing.](image)

4.2  Abutment near Green Island, Jamaica (1999)

A 30 foot tall abutment was constructed near Green Island, Jamaica as part of an island-wide highway upgrade initiative through design-build contracting. Initially, the West abutment of the bridge was to be founded on piling. The design-build contractor from Korea was unable to get the required equipment to the abutment site, which was in a mangrove swamp overlying 27 m (90 feet) of zero blow count alluvial silt. Layers of geotextile and marl fill provided access to the site and also as the abutment material. The abutment was constructed in lifts to allow pore water pressures to dissipate, and settled globally approximately 60 cm (24 inches). A surcharge was added to simulate the load of the bridge deck. During the process, currency fluctuations and political factors resulted in a change in the international design-build contractor. The new design team was unfamiliar with GRS-IBS technology and opted to abandon the abutment and construct a traditional pile founded bridge at nearly 3 times the cost. This project demonstrated that with proper
construction staging and surcharge loading, the GRS-IBS system can be installed on the weakest of soils.

Figure 7 - Green Island Bridge under construction. The construction was nearly all completed using local unskilled labor and hand tools.

Figure 8 - View of abutment after completion of surcharge loading.
4.3 Bridge near Mammoth Lakes, CA

An historic bridge near Mammoth Lakes, CA required replacement due to structural deficiencies of the superstructure. Moreover, the abutments and pillars were of unknown quality but were required to be preserved for aesthetic and historic reasons. After the original superstructure was removed, the area behind the abutment walls was excavated and replaced with GRS composite. A new deck was placed on the GRS composite so that with full loading the deck would not touch the existing pillars. The end result was a modern GRS-IBS bridge that appeared to be resting on historic abutments and piers. This project demonstrated the flexibility of the GRS-IBS system and the cost savings associated with leaving existing abutment walls in place.

![Mammoth Lakes bridge](image)

*Figure 9 - Mammoth Lakes bridge. Note that the deck clears the historic piers by approximately 4 inches.*

4.4 Private Development Access Bridge near Big Sky, MT (2001)

Access to a private development crossed a protected stream and terminated on an ancient landslide in one of Montana’s highest seismic zones. Traditional bridge options required piling and post-tensioned ground anchors. The GRS-IBS approach spanned the gorge with a 58 m (191 foot) single span steel girder bridge founded on GRS abutments, at approximately 25% the cost of the traditional solution. Post construction settlement has been negligible, even after the owners placed a 45,359 kg (100,000 pound) decorative timber cladding on the bridge in 2004. To the authors’ knowledge, this is still the longest GRS-IBS bridge in the world.
4.5 Ruple Park, Ohio Bin Wall Repair (2014)

A deteriorated bin wall that supported Ruple Parkway in the City of Brook Park, Cuyahoga County, Ohio was repaired in place using self-drilling soil nails to penetrate the existing retaining wall and anchor into the embankment fill behind. The new soil nail wall was designed to neglect the structural contribution of the existing retaining wall. Since the original retaining wall geometry was used, it essentially performed as temporary shoring for the new wall construction, thereby eliminating considerable construction costs that are typically associated with replacing retaining walls with traditional technologies.
4.6  KY 987 MP 7.1 Bell County (2013)

An approximately 27 m (90 foot) long slide closed the roadway in May 2013. A combination of soil nails to restrain the remaining embankment, micropiles (to support the weight of the GCS buildout) and a GCS embankment section were utilized to reconstruct this slide in a 3 week timeframe.

5.0  CONCLUSION

As the geotechnical industry has evolved over the past 50 years, many new tools and techniques have been developed. The combinations demonstrated herein have proven effective for remediating numerous types of geohazards including failing earth retention systems, for embankment stabilization, and for rapid bridge construction methods. These methods have been widely adopted in the highway, railroad, and energy industries, and have considerable application to coal ash waste management as well as other areas of the power-generation and transmission sectors. Stabilization of ash impoundment embankments, installation of horizontal drains, haul road stabilization and bridge construction are a few of the potential applications for these technologies.
6.0 REFERENCES


