



Soil Mix Shear Keys at Dam Toe in Peat

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ABSTRACT

In 2017, In Situ Soil Mixing (ISSM) with cement was used to increase the shear strength of soft soils, including an organic peat layer, at the toe of an existing tailings dam.

The ISSM soil-cement shear key elements were installed at the subject site using a track-mounted large-diameter single-auger soil mix drill rig fed with a simple grout consisting of water and Portland cement. A total of 76 individual shear key elements were installed perpendicular to the dam alignment. Each shear key element consisted of 3 overlapping soil mixed columns advanced to a maximum depth from ground surface of 12.8 m.

Based on the final column layout, the target (UCS) for soil mixed elements was 1.43 MPa or greater. Quality control testing on wet grab samples confirmed the average actual UCS was 7.01 MPa after 28 days of curing. Sonic cores were also collected for visual observation.

As performance requirements were readily surpassed, the project demonstrates the viability and cost-effectiveness of performance-based in-situ soil improvement using ISSM, even where problematic materials, such as peat, are present.

RÉSUMÉ

En 2017, le mélange de sol in situ (ISSM) avec du ciment a été utilisé pour augmenter la résistance au cisaillement des sols mous, y compris une couche de tourbe organique, au pied d'un barrage de résidus existant.

Les éléments clés de cisaillement sol-ciment de l'ISSM ont été installés sur le site en question à l'aide d'un appareil de forage de mélange de sol à large vis et grand diamètre alimenté par un simple coulis composé d'eau et de ciment Portland. Un total de 76 éléments de clé de cisaillement individuels ont été installés perpendiculairement à l'alignement du barrage. Chaque élément clé de cisaillement consistait en 3 colonnes mixtes de sol se chevauchant et poussant jusqu'à une profondeur maximale de 12,8 m.

Selon la disposition finale des colonnes, la cible (SCU) pour les éléments mélangés au sol était de 1,43 MPa ou plus. Des tests de contrôle de la qualité effectués sur des échantillons de grappes humides ont confirmé que le SCU réel moyen était de 7,01 MPa après 28 jours de durcissement. Les carottes soniques ont également été recueillies pour l'observation visuelle.

Comme les exigences de performance ont été facilement dépassées, le projet démontre la viabilité et la rentabilité de l'amélioration du sol in situ basée sur la performance en utilisant ISSM, même là où des matériaux problématiques, tels que la tourbe, sont présents.

1 INTRODUCTION

In late 2016 / early 2017, a mining facility in Ontario determined that some of its historic earthen embankments did not meet current regulatory stability requirements. Once this determination was made, the facility began researching methods of bringing these embankments into compliance.

The extremely soft soils including mine tailings and peat/muskeg/fibrous organics at this site, can be problematic for ground improvement methods that rely on compaction, such as stone columns. In situ soil mixing (ISSM) with cementitious materials, an alternative to compaction-based methods, is frequently employed to directly improve the compressive, and to a lesser degree, tensile strength of soils (See, e.g., Mitchell, 2008, Adams 2011, and Filz and Bruce, 2016). This method can be used to install transverse shear walls in earth fill dams, embankments, dykes or levees. In this method, the existing soils are mixed with a cementitious material, such as Portland cement (PC), and allowed to cure.

After thorough analysis, ISSM was selected as the primary improvement method for bringing the existing

embankments into compliance, followed by aggregate fill placement above it in subsequent project phases. The ISSM at this site was to be used to install a shear key at the tailings dam toe, through tailings, organic soils, and soft clays, into a relatively stiff till layer. As shown in this case study example, the ISSM method can be efficiently and effectively used to retroactively install shear walls in legacy structures, bringing them up to contemporary standards.

2 DESIGN

The design for this project stipulated that the ISSM would need to provide an equivalent strength to a 4 metre (m) wide continuous soil mix wall, with a minimum undrained shear strength of 650 kilopascals (kPa). This design was based on static, limit equilibrium analyses of multiple failure modes to increase the factor of safety (FOS) for slope stability by intersecting expected failure planes.

3 CONTRACTOR SELECTION

In the Spring of 2017, the facility released a request for proposal (RFP) for competitive bids for the planned ISSM work. Canada Geo-Solutions, Inc a wholly owned subsidiary of Geo-Solutions, Inc, jointly referred to herein as GSI, was the successful respondent to that RFP and ultimately performed the work.

Consistent with general design recommendations (FHWA, 2013) allowing for individual contractor equipment and experience, GSI proposed a 7.2-meter wide improvement zone, with individual shear key elements formed by three overlapping 2.6-m diameter soil mix columns along an axis perpendicular to the dam centerline. Subject to layout constraints, such as following curved sections of the dam alignment, the design used a shear wall center-to-center spacing of approximately 4.0 metres. Using the proposed areal replacement ratio (~53%), the stability requirements were met with a target unconfined compressive strength (UCS) of 1.43 MPa, with the conversion from shear strength to UCS completed using general industry guidance (Andromalos et. al. 2000 and FHWA, 2013).

The “wall” configuration, as opposed to installation of simple columnar structures, was selected to resist columnar flex or the “bending” of isolated piles and columns. Because of the relatively high area replacement ratio and close wall spacing, a unifying “backbone” wall parallel to the dam alignment was not utilized.

While the proposed ISSM method avoids issues related to compacting extremely soft material, the presence of peat (or other extremely high-organic content soil) can interfere with cement curing. Low pH, calcium scavenging by humic acids, a relative scarcity of mineral (clay) content to support secondary pozzolanic reactions, and other factors interfere with strength gain. To address potential issues associated with the peat layer, GSI proposed pre-excavation of the peat ahead of soil mixing under a support slurry.

4 BENCH SCALE STUDIES

As mentioned previously, high organic content soils, particularly peat, are known to adversely affect the curing of soil-cement. Bench top testing was performed to verify the feasibility of the proposed method and determine the target dose of general use (GU) Portland cement per unit volume of soil. Samples of site soil were obtained by the facility and shipped to GSI. The samples were labeled in groups of soils from the distinct horizons, i.e. tailings, peat/organics, silt/clay. Upon receipt, GSI subjected the soil samples to basic laboratory analysis for determination of “index” properties. The average index properties for each soil layer are provided on Table 1.

After index testing, soil-grout mixtures were created using methods that mimic a standard field mixing process (Andromalos et al 2015). For the first round of mixes, three representative composites, one for each of the major stratigraphic units above the foundational till: tailings, peat/organics, and silt/clay, were created and used to formulate four soil-grout mixes each. For these initial mixes, the cement content, by weight of soil, was varied

from 10% to 40% and the mixes were created using the same grout consistency with a water to cement ratio (W:C) of 1:1.

Table 1. Summary of average soil index properties by soil layer

Soil Type	Soil Properties				
	% Fines	% Organics	pH	LL	PI
Tailings	98.6	0.5	7.5	34	7
Silt/Clay	97.8	1.3	7.6	27	7
Peat/Organics	71.2	48.1	7.1	NP	NP

Specimens of each mixture were allowed to cure in a temperature controlled environment and were then subjected to Unconfined Compressive Strength (UCS, ASTM D1633/D2166) testing. The 28 day strengths ranged from approximately 1500 to 4000 kPa for the mixes created from the tailings, from 150 to 300 kPa for the mixes created from the organics, and from 1100 to 2000 kPa for the mixes created from the silt/clay. The 28 day strengths were approximately 2.5, 1.9, and 1.6 times the 7 day strengths for the mixes created from the tailings, organics, and silt/clay, respectively. These initial results led to GSI's decision to pre-excavate the high-organic (peat) material, as it would be cost-prohibitive to overcome this material's effects with additional cement.

Immediately prior to construction, a second round of bench scale testing was performed to assess the impact of incomplete organic removal before soil mixing, the addition of bentonite during pre-trenching the addition of aggregate backfill during pre-trenching, and to confirm the findings of the first round of testing. Composite samples of blended soil types were created as depicted in Table 2.

Table 2. Supplemental Test Composite Samples

Description	Soil Composite 1	Soil Composite 2
	Complete organic removal / best case	Poor organic removal / worst case
Tailings	13%	28%
Organics	0%	19%
Granular Backfill ¹	34%	17%
Silty Clay	53%	37%

¹ The granular backfill used in this study was a 50/50 mixture, by weight, of small gravel (12.7mm/0.5" minus) and masonry sand.

To simulate the pre-excavation of peat under a support slurry, the samples were mixed with a small amount of bentonite slurry and varying proportions of cementitious materials (cement alone or a combination of cement & slag) with a total cementitious reagent addition that ranged from 18% to 26%.

Once cured, these additional mixes were again subjected to UCS testing after 7, 14, and 28 days of curing. The 28 day strengths ranged from approximately 2000 to 4500 kPa for the mixes created from Soil Composite 1 and

700 to 1400 kPa for the mixes created from Soil Composite 2. The 28 day strengths were approximately 1.8 and 1.4 times the 7 day strengths for the Soil Composite 1 and Soil Composite 2 mixes, respectively.

The second round of mixes confirmed the importance of removing the organic material as evidenced by the relative performance of the mixes created using Soil Composite 2 vs. Soil Composite 1.

Based on the results from both rounds of bench scale testing, GSI selected GU Portland contents of 22% and 26% for further evaluation in a full scale test program.

5 CONSTRUCTION

5.1 Full Scale Test Program

Six test columns were installed prior to the start of production column installation, using the same methods intended for the production columns with varying parameters such as cement addition rate and pre-excavation methods. Three wet grab sample sets were collected from each column for UCS testing. These wet grabs were collected from the test columns using a hydraulic soil mix sampler at depths above the organic layer (expected to be substantially the sand / spoils used to backfill the pre-excavation); from within the organic layer (presumably mostly backfill material, but likely some organics entrained); and finally below the organic layer in the soft clay.

Post installation, the columns were allowed to cure for a period of two weeks and were then subjected to sonic coring. The sonic cores were used to assess mixing uniformity and cement distribution. Following coring, the columns were destructively excavated for visual inspection (see Figure 1).

Cement addition rates of 22%, 26%, and 30%, by weight, were evaluated in the test column program, and calculated using an estimated soil density of 1.92 tonnes/m³.

All the test program column samples analyzed met the strength requirements. The test columns themselves passed visual inspection during coring and destructive evaluation. After 7 days of cure, the highest UCS test result observed in a wet grab sample was 1051 kPa, from a column using 22% cement and a 0.8:1 W:C. After 14 days, the highest test result (1464 kPa) was observed in a sample from a column using 22% cement and a 1:1 W:C. The final results of the test program indicated that a 22% cement addition rate, by weight of soil assuming a in situ density of 1.92 tonnes/m³, delivered in a grout with a water to cement ratio of less than 1:1 W:C, would achieve the project requirements by an appropriately conservative margin.

5.2 Pre-Excavation

At areas along the dam alignment where a high organic/peat layer was identified, GSI had planned on performing pre-excavation of the organics under a bentonite support slurry. As the project progressed, it became clearly advantageous to reduce the amount of bentonite slurry and instead use excess uncured (wet) spoils/swell from prior columns, to the extent feasible, to improve trench stability. To accomplish this, the pre-excavation excavator operator would reach over into fresh soil mixed material and "spoon" material over into the advancing pre-excavation. This had the additional advantage of reducing excess spoils ("swell") returned to the ground surface during the mixing process. The cement in the recycled spoils was not credited against (did not affect) the cement content calculated for delivery to new



Figure 1. Excavated Test Program Columns

shear walls, but probably benefited the project by helping to tie up any remaining organics post pre-excitation.

Excavation under slurry/fresh spoils continued until the organic material was removed and the clay/silt layer beneath was reached. Backfill material consisted of the segregated inorganic soils from the excavation, soil mixing spoils, and imported make-up granular material provided by the facility. Figure 2 includes a photo of an ongoing pre-excitation cell and Figure 3 shows an example of the organic material removed.



Figure 2. Pre-excitation

5.3 Shear Key Elements

While the test columns cured, i.e., prior to final results, GSI began shear wall installation at-risk using a conservative 26% cement dosage delivered in a 0.8:1 W:C after pre-excitation of the organics.

Over the course of the project, 76 individual shear key elements were installed perpendicular to the dam alignment. Each shear key element consisted of 3 overlapping soil mixed columns advanced to an average depth of approximately 10m and a maximum depth of 12.8m, both measured from ground surface.

Each column center was surveyed in the field using a global positioning system (GPS). The existing ground elevation was recorded on the driller's log for the determination of the top and bottom of the column. The drill rig was then plumbed and positioned over the column center to commence column drilling. Using the existing ground elevation as a reference, the auger was advanced to the design top of column (TOC) elevation, often not the same as the work platform elevation. The driller re-zeroed his depth gauge and began the electronic recording of the drilling phase.

The drill rig utilized was a Delmag RH-18, equipped with a 2.59m diameter single flight auger mounted on the end of a hollow stem Kelly bar. The rig and auger were able to introduce grout at the point of mixing through a series of ports on the back of the auger flights. The auger was also outfitted with replaceable cutting teeth which were changed throughout the project as needed, to maintain proper cutting and mixing of the soil. Figure 4 includes a photo of the drill rig and auger used for this project.



Figure 3. Organic material removed during pre-excitation

The water and grout were supplied by an automated batching plant with associated delivery pumps. The batch plant mixed Portland cement with water to form a grout. The grout was then pumped to the drill rig for column mixing. The drill rig operator was in constant communication with the plant operator to control the delivery rate of the drilling fluid, modified as needed to accommodate drilling conditions. Batching processes and measurements were configured to err on the side of conservatism, i.e., the actual cement dose, if it varied from the design dose, was purposely forced to result in excess cement added.

Three columns were overlapped to form each shear wall. Data from the drill rig's electronic data recording system was used to verify the number of mixing passes, volume of grout delivered, and auger rotation speed. When complete with a shear wall, the soil mix drill was tripped out of the wall and tracked over to the next nearest wall location.

As discussed, initially, a conservative cement addition of 26% Portland, delivered in a 0.8:1 water-cement ratio grout, was utilized. Once the results from the test columns were received and reviewed, the cement addition was reduced to 22%, delivered in a 1:1 water-cement ratio grout.

5.4 Quality Control

Daily quality control reports detailed the work completed on each column and the quality control (QC) testing utilized to control the grout proportions at the batch plant. The daily reports summarized the column depth, drilling rate, and volume of fluid mixed in each column. Daily QC also included field tests performed on the grout at the batch plant, which were used to ensure cement content, including density, viscosity, temperature, and pH.

At the soil mixing rig, wet "grab" samples of the freshly mixed soil and grout were collected at a minimum frequency of one set every 200m³ of mixing or once per shift, whichever was more frequent. The samples were collected from discrete locations in the column using the hydraulic sampler discussed above. The depth of each sample, selected in consultation with the engineer's representative, was varied to obtain results from below, above, and within the organic layer.

Wet grab sample material was then processed through a 12.7mm opening screen to remove rocks and debris, and cast into 51mm by 102mm plastic cylindrical molds. The plastic molds were stored onsite in an insulated, moisture controlled environment to allow the soil mix to take an initial set. Once the samples had cured for 3 to 5 days, they were delivered to a third party laboratory for UCS testing after 7, 14, and 28 days of curing.

A coring program was also used to allow qualitative assessment of mixing extent and homogeneity. Sonic coring was selected as the coring approach because it guaranteed nearly full recovery. However, sonic coring does not yield an intact sample and, in fact, on a brittle material like soil mixed with cement, the resulting recovered sample is usually highly fractured. Production cores were therefore not subject to UCS testing, but were compared with the coring results from the test columns that were validated through additional assessment methods, including destructive over-excavation.

Cores were collected using a Sonic Drill Systems 550 track-mounted drill rig and the drilling was performed "dry" (water was not used as a drilling fluid). The recovered core was subject to photo-logging and visual inspection for comparison to the test column cores and to detect evidence of inadequate mixing, such as large clods of clay, or areas without cement.



Figure 4. Large Diameter Auger with Grout Ports

6 RESULTS

6.1 Final Compressive Strengths

Based on the final column layout, the target (UCS) for the soil mixed elements was 1.43 MPa or greater. The average actual UCS of wet grab samples from the stabilized soil was approximately 7000 kPa after 28 days of curing and, on average, the 28 day strength was 1.4 times the 7 day strength. The coefficient of variation (COV) which is the ratio of the standard deviation to the mean, is a common measure of property variability on soil mixing projects. For the wet grab UCS data set, the COV was 0.29. A portion of the samples subjected to UCS testing after 112 days of curing showed strength improvement of approximately 20% after 28 days of curing. Figure 5 shows the strength development curve of these samples with average and standard deviations.

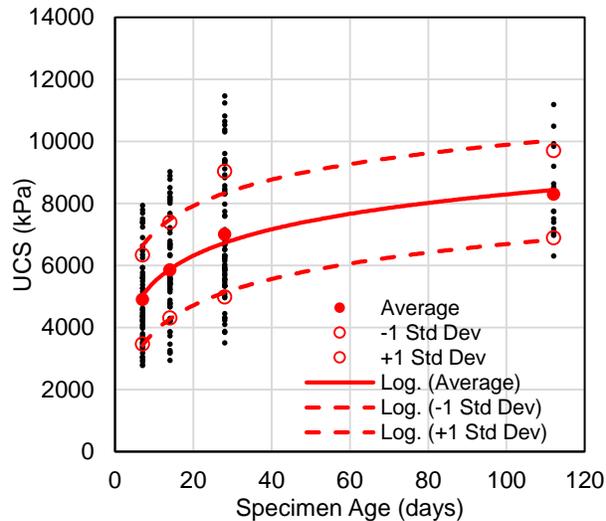


Figure 5. UCS vs specimen age

6.2 Visual Examination

Eight of the 228 production columns (3.5% of production columns) were cored. Results were correlated to observations made during destructive over-excavation of the test columns. The eight cores showed good core recovery, good homogeneity, with consistent mixing into the lower contact of the column.

7 CONCLUSIONS

Given the commercially competitive price, final UCS and mixing uniformity data, and the related inferred increases in shear strength, the project demonstrates the viability and cost-effectiveness of performance-based in-situ soil improvement using ISSM, even when problematic materials such as peat are present.

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