Remediation of Soft Clay Utilizing the “Dry Mix Method”

Introduction

Tonawanda Creek meanders as it flows in a generally westerly direction from its headwaters east of Batavia, New York to its discharge into the Niagara River at Tonawanda, New York. The geologic conditions along Tonawanda Creek have historically contributed to a number of bank failures that have damaged pavements and threatened homes constructed along the creek. The western portion of the creek flows through soft lacustrine clay soils that extend to a depth of about 30 to 50 feet. Subsequent glacial deposition resulted in a layer of sand and silt above the soft clay along the banks of Tonawanda Creek. The meandering creek causes erosion that eventually results in a loss of support for the creek banks. This effect, coupled with saturation of the upper silty soils due to rain events and poor drainage, is the cause for many of the slope failures along Tonawanda Creek.

Two slope failures along Tonawanda Creek have been investigated; one in Niagara County by the US Army Corps of Engineers and one in Erie County by the Erie County Department of Public Works. Site investigations included borings with in-situ strength testing, and installation of instruments including vibrating wire piezometers and inclinometers. The investigations revealed that the soft clay soils are sensitive, losing strength as they deform. Research into remedial methods revealed that soft sensitive clays have been remediated in Scandinavia for the past 25 years by mixing dry cement or lime with the soft clay to depths of 50 feet or more. This process, known as the “dry mix” method, has been used on a few projects in the United States and was selected for remediation at these two sites. This paper describes the testing and engineering analysis that led to the selection of the “dry mix” process and the use of this approach to remediate these two sites in 2008 and 2009.
Geologic Conditions along Tonawanda Creek

Tonawanda Creek flows in a generally westerly direction from its headwaters east of Batavia to its discharge into the Niagara River at Tonawanda, New York. Figure 1 is a plan showing a section of the western portion of Tonawanda Creek near Transit Road. Tonawanda Creek Road exists on both sides of Tonawanda Creek, one in Erie County and one in Niagara County.

![Figure 1](image)

**Figure 1**

The western portion of Tonawanda Creek flows through soft clay soils that were deposited during the last glacial period. As the glacial ice retreated, a lake (Lake Tonawanda) was impounded between the glacial ice and higher ground to the south. Soft clay was deposited on the bottom of the lake and remained after the glacial ice and lake waters receded. Subsequent deposits resulted in a layer of sand and silt above the soft clay along the banks of Tonawanda Creek.
Site Conditions

This paper discusses two slope failures along Tonawanda Creek; one in Niagara County investigated by the US Army Corps of Engineers and one in Erie County investigated by the Erie County Department of Public Works.

In 2004, a slope failure along the south bank of Tonawanda Creek in Erie County damaged a portion of Tonawanda Creek Road between Transit Road and Westphalinger Road in the Town of Clarence (see Figure 1). A section of Tonawanda Creek Road, approximately 250 feet long dropped about 10 feet and pushed soil into Tonawanda Creek as shown on Figure 2.

![Figure 2]

Beginning in 1994, a continual failing slope along the north bank of Tonawanda Creek in Niagara County damaged a portion of Tonawanda Creek Road near Minnick Road in the Town of Lockport (see Figure 1). A section of Tonawanda Creek Road approximately 100 feet long continued to drop damaging an existing culvert underneath the roadway.
Subsurface explorations indicate similar subsurface conditions at the two sites. Explorations included collecting Standard Penetration Test (SPT) split spoon samples and thin walled tube samples (Shelby tubes) of the overburden soils and core samples of the rock. Testing included in-situ vane shear tests (VST's) to estimate the shear strength of the soils and laboratory tests, including grain size distribution, moisture content tests and Atterberg Limits.

Figures 3 and 4 are logs of two borings that illustrate the typical subsurface conditions and the test results at the sites. The figures summarize the SPT-N-value with depth, moisture content profile, VST results (peak and residual), Atterberg limit data and a generalized soil description.

In general, a few feet of fill is present at each site. Beneath the fill, a silty sand deposit extends to a depth of about 10 feet. Boring logs from the two sites describe this soil as either sand, silty sand or silt depending on location. Because of the relatively high silt and fine sand percentage, the silty sand drains slowly, contributing to the unstable slope conditions along the creek.

Beneath the silty sand is a deposit of soft to very soft clay that extends to about 35 feet deep. The soft clay covers a glacial till deposit, a mixture of gravel, sand, silt and clay with boulders and cobbles. The glacial till deposit is relatively loose for about the upper 5 feet, and then becomes dense or hard, based on the SPT N-values that generally range from about 40 to more than 100. The top of bedrock was observed at a depth of about 68 feet at the Westphalinger site and at a depth of 59 feet at the Minnick Road site. Bedrock is of the Camillus Formation and is a medium hard to hard dolomitic shale with gypsum deposits.
Figure 3 – Typical Westphalinger Road Boring
Figure 4 – Typical Minnick Road Boring
The thickness and consistency of the soft clay layer are important factors in the stability of slopes along Tonawanda Creek. The SPT N-values range from WR (weight of rods) to WH (weight of hammer), signifying that the weight of the drilling rods or the weight of rods and hammer in the borehole was sufficient to advance the split spoon sampler the specified 24-inch distance. VST measurements of the peak shear strength of the soft clay ranges from 228 to 608 pounds per square foot (psf) with a remolded strength between 35 and 186 psf. The ratio of the peak to the remolded strength varies from about 2.5 to 10 indicating that the soft silty clay is slightly to moderately sensitive. The moisture content of samples of the soft silty clay layer are close to or greater than the liquid limit, a characteristic that is common to sensitive soils. The groundwater level in the soft clay soil coincides with the top of the soft clay deposit. Perched groundwater is present in the sand and silts above the soft clay.

**The Problem**

Tonawanda Creek’s meandering flow pattern results in erosion of the stream bank on the outer bend in the creek and deposition on inside bends of the creek. Erosion of the outer creek banks over time results in a loss of support for the banks. During wet times of the year, the upper silty soils become saturated due to rain events and poor drainage. Failures occur where the soft clay soils are too weak to support the increased weight of the saturated soil, especially where there has been a loss of toe support. This is the reason that most of the failures occur during the spring or early summer along bends in the creek. The result is a failure through the soft clay with the soft soil pushing up and out into the creek as shown on Figure 5 (stream bank located in upper right hand corner).
Figure 5

Consideration of Remedial Options

Stabilizing this condition requires creating a stable base upon which to reconstruct the road embankment. In general, the stability of slopes can be improved in four ways:

- modifying the slope geometry,
- providing or improving surface and or subsurface drainage,
- providing internal slope strengthening/reinforcement and,
- constructing a retaining structure.
Modification of Slope Geometry

Modification of slope geometry to improve stability may include flattening the slope, adding weight to the toe of slope or removal of weight from the top. Removing weight from the top of the slope would require lowering the road and was not a feasible option at either site. Similarly, adding weight to the toe would require constructing a berm that extends into the creek, also not a feasible option. Because the clay has such low strength, stability calculations indicate that flattening the slope to 10 horizontal to 1 vertical is necessary for a factor of safety of about 1.5. Due to the limited area between the roadway and stream channel, and the vicinity of nearby residents, this option is not realistic at either site.

Surface and Subsurface Drainage

Improving the stability of both sites by improving the surface drainage and providing subsurface drainage for the upper sandy silt deposit is an important part of the remedial plan for each site. High groundwater levels in the upper sandy soil is a contributing factor to the slope failures therefore, improving the surface drainage to limit infiltration into the sandy soil and providing subsurface drainage to keep it drained are important components of the remedial design. Stability calculations indicate that providing better drainage improves the slope stability but does not provide a sufficient margin of safety against future failures. Therefore, the drainage improvements must be done in conjunction with other measures to improve the slope stability.

Internal Slope Strengthening

Internal slope strengthening involves improving the shear strength and reducing the compressibility of the soil within the failure zone. Examples of this include installing stone columns through the failure zone, injecting dry cement or grout (i.e. dry or wet soil mixing) into the failure zone or using reaction blocks and anchors to compress the soil and increase its strength and resistance.
Stone columns were evaluated but the number of columns required would be prohibitive at this site. We also rejected reaction blocks and anchors because the soil is too weak to provide sufficient reaction and extending the anchors to rock would require 100-foot long anchors.

Wet and dry soil mixing was considered. The wet mixing involves mixing cement grout with the in-situ soil. The resulting column strengths are on the order of several hundred pounds per square inch (psi), however there is a significant amount of waste associated with this process. Dry mixing yields a column that is not as strong as wet mixing, (typically on the order of 50 to 60 psi) but there is virtually no waste. Considering that the columns must be spaced closely enough to provide uniform support for the road embankment, the higher strength columns afforded by the wet process are not necessary. Because the dry columns provide sufficient strength with no waste, we selected this method for further evaluation as described in the following section.

*Retaining Structures*

Retaining walls can be used to provide lateral resistance against slope movement. At both sites the wall would have to be approximately 35 feet deep to provide the necessary resistance. Driven sheet piles or drilled in soldier piles and lagging are the two types of walls considered feasible. This would involve driving sheet piles or drilling soldier piles through the soft silty clay and into the glacial till. Due to the low strength of the very soft silty clay, the top of the wall would have to be restrained with anchors that extend diagonally to rock, making them approximately 100 feet long.

Pile driving induces vibrations that can weaken the sensitive silty clay soils leading to instability and movement of the wall during installation. Figure 6 shows a wall under construction on Tonawanda Creek where the top of the sheetpiles moved and the slope behind the wall dropped
during installation. Because of concerns about stability during construction and the length and expense associated with the anchors, the wall was not considered a viable alternative.

![Figure 6](image)

**Figure 6**

**Slope Stabilization Approach**

The approach selected for remediation involves providing additional subsurface and surface drainage and strengthening the soft soils with soil cement columns. Drainage improvements are incorporated into the design to limit the build-up of groundwater in the silty sand soils that overlie the soft clay. The soil cement columns extend through the soft clay to the hard glacial till providing support for the road embankment.

The soil cement columns are constructed using the “dry mixing” method. This method was developed in and is used throughout Northern Europe and Japan to improve the engineering properties of soft clays, peats and other weak soils. The process uses cementitious powders to bond soil particles, thereby increasing the shear strength and reducing the compressibility of the soil. Dry mixing is often used in high groundwater conditions and has the advantage of
producing no spoil for disposal. Using specialized mixing equipment; the soil is mixed during penetration, until the mixing tool reaches the maximum treatment depth. Dry binder agents are injected into and mixed with the soil during withdrawal of the mixing tool, leaving behind a dry soil mix column. The general process is shown on Figure 7.

![Figure 7](image)

The strength of the soil cement column is dependent on the type of soil and the amount and type of binder used. Typical binder agents include cement, lime, gypsum, slag or a combination. The strength and stiffness of the soil cement column generally increases with increasing binder dosage. The binder dosage rate typically ranges between 80 pounds per cubic yard (lb/yd$^3$) (50 kilograms per cubic meter (kg/m$^3$)) in soft clays to as high as 450 lb/yd$^3$ (270 kg/m$^3$) in peat. Shear strengths in different types of soils and binder dosage rates are shown on Figure 8.
Soil mix column diameters of 2 to 3 feet can be constructed to depths of 60 feet. Soil mix column strengths typically are 10 to 50 times stronger and much stiffer than the native soils. Figure 9 shows the interaction between the native soils and dry mix columns (shown as springs). The columns transfer most of the embankment load to the stiffer underlying layer.

Cost comparisons indicate that the dry mix method is less expensive than either stone columns or wet soil mixing and is comparable to the cost of a tie-back sheet pile wall.
Laboratory Testing and Test Pad

Laboratory tests and a test pad were completed to evaluate the column strength that could be achieved using soil from the Minnick Road and Westphalinger sites. We collected Shelby tube samples of the soft clay and shipped them to Geotesting Services, Inc. (Geotesting) for testing. Geotesting added dry cement and a combination of dry cement and lime at various addition rates to the soft clay, allowed the mixture to cure and then measured the compressive strength of the mixture at 7, 14, 28 and 57 days. The following table is a summary of the mix proportions and strength results obtained during the laboratory investigations completed for the Westphalinger Road site. The laboratory results indicate that a cement addition rate of 75 kg/m³ would provide a soil-cement column shear strength between 6,000 and 8,000 psf.

<table>
<thead>
<tr>
<th>SAMPLE NO.</th>
<th>SOIL ADDITIVES</th>
<th>POUR DATE</th>
<th>CURING PERIOD</th>
<th>WATER CONTENT</th>
<th>TOTAL UNIT WGT. (pcf)</th>
<th>DRY UNIT WGT. (pcf)</th>
<th>PEAK COMRESSIVE STRESS (psi)</th>
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<td>75 Cement 75 Lime 25</td>
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<td>110.0</td>
<td>76.7</td>
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<td>109.8</td>
<td>75.7</td>
<td>36.4</td>
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<td>109.3</td>
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<td>Mix 4</td>
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<td>109.3</td>
<td>76.1</td>
<td>83.1</td>
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</table>

To verify the suitability of the dry mix method, Hayward Baker Inc. (Hayward Baker) was retained to mobilize its dry mix equipment and install 12 test columns at the Westphalinger Road site. We monitored the column installation and the cement addition rate, drilled borings into the completed columns and collected Shelby tube samples for strength testing. The test results indicate shear strengths between about 2,000 and 4,000 psf, which are lower than indicated by
the tests on the laboratory mixes. The lower values could be due the difficulty in collecting undisturbed samples of the completed columns or actual differences between the strength achieved in the field compared with that in the laboratory.

To provide another means of measuring the strength of the completed columns, Hayward Baker installed vanes in several columns. A metal vane is attached to a steel cable that is inserted during the initial penetration of the mixing apparatus. The steel cable extends from the vane at the bottom of the column to the ground surface. Several days after installation, the vane is pulled up through the center of the soil-cement column. The column shear strength is estimated based on the force required to pull the vane, the vane area and a bearing capacity factor. A schematic of the vane test is shown in Figure 10. The vane results indicated column shear strength values in excess of 8,000 psf.

![Figure 10](image)

**Design Plan**

The spacing of the soil-cement columns and the appropriate mixture of cement and soil are dependent on the site soil conditions. The lab results did not show a benefit of using quicklime, therefore the design considers adding only cement. Based on the laboratory and test pad results,
we selected a cement addition rate of 75 kg/m$^3$, which is equivalent to mixing 8 to 10 bags of dry cement (Type I cement) with the soft clay in a hole that is 30 inches in diameter and 30 feet deep.

We based the column layout on a weighted strength using a conservative estimate of shear strength for the treated area of 2,000 to 3,000 psf and the in-situ vane shear strengths for the untreated area. We completed slope stability analysis using the estimated weighted average strength and varied the column layout to achieve a calculated factor of safety of 1.5.

The following table is a summary of the design layout for each site and Figure 11 is a plan and section of the column layout for each site. As indicated, the percentage of area treated at the Westphalinger site is significantly greater than at the Minnick site. This is because the remolded strength was factored into the design at the Westphalinger Road site since the slope had experienced substantial movement. The Minnick site did not experience movement of the magnitude that occurred at the Westphalinger site, therefore, we based the design on the peak shear strength. This resulted in a lower treatment percentage at the Minnick site.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minnick Road Site</th>
<th>Westphalinger Road Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Soil-Cement Column (inches)</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Number of Columns</td>
<td>651</td>
<td>2,227</td>
</tr>
<tr>
<td>Roadway Length (ft)</td>
<td>200</td>
<td>570</td>
</tr>
<tr>
<td>Area Treated with soil-cement columns (%)</td>
<td>38</td>
<td>58</td>
</tr>
<tr>
<td>Blade Rotation Number$^1$</td>
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<td>400</td>
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</table>

Table Note: 1. The blade rotation number is the total number of mixing blades passing during 3.28 feet (1 meter) of mixing tool extraction.
Figure 11

TYPICAL MINNICK ROAD
SOIL-CEMENT COLUMN
LAYOUT PLAN

TYPICAL WESTPHALINGER
ROAD SOIL-CEMENT COLUMN
LAYOUT PLAN

TYPICAL SECTION A-A
As shown on Figure 11, the columns extend from the top of the soft clay layer to the top of the glacial till. The majority of the columns are directly beneath the roadway to transfer the embankment load to the glacial till layer. The soil-cement columns are effective when under compressive loading but not effective when placed in shear or bending configurations. Therefore, the layout has the columns in a continuous wall pattern, perpendicular to the direction of the road. This puts the columns primarily in compression and limits bending and shear stresses on the columns. Additionally, a strength reduction factor is applied to columns outside the embankment (between the roadway and creek).

The Westphalinger design also includes a mechanically stabilized earth wall through the failure area. The wall limits the aerial extent of the road embankment, reducing the required treatment area. Under drains and improved surface drainage are included in both designs to limit groundwater build-up in the silty sand.

**Construction**

Hayward Baker, as a subcontractor to Nichols Long and Moore Construction Corp., completed column installation at the Minnick Road site in the summer and fall of 2008. Hayward Baker completed column installation as a subcontractor to Accadia Site Contracting, Inc. at the Westphalinger Road site in the winter and spring of 2009, when construction activities are normally prohibited by weather.

At each site, a precut was made to offset the weight of the proposed dry mixing equipment. Figure 12 shows a picture of the dry mixing apparatus consisting of a mixing rig, concrete
storage shuttle and a compressor. Figure 13 shows a picture of the dry mixing rig and mixing apparatus.

The dry soil mixing process induces air pressure into the soil that creates an increase in pore pressure and corresponding loss in soil strength. If not controlled, this can lead to slope failure during construction. Dissipation of the induced pore pressures takes several days, therefore the work must be sequenced to allow the pressure to dissipate before continuing work in an area. Inclinometers and vibrating wire piezometers were installed at the Westphalinger site to monitor the pore pressure build-up and provide information necessary to develop an appropriate work sequence. Additionally, the slope at each site was monitored for movement using a series of survey hubs between the treated area and Tonawanda Creek. At the Minnick Road site more than 2 feet of lateral movement occurred on the slope between the work area and the creek during the column installation. Movement was not observed on the work platform or on the backside of the road. Therefore, no impact was suspected on the design/performance of the dry mix columns.
Soil-Cement Column Results

Three sampling methods were employed to estimate the strength of the soil-cement columns. Earth Dimensions, Inc. drilled borings in completed columns and collected Shelby tube samples for unconsolidated undrained (UU) triaxial testing. Difficulties in maintaining the hole within the column for its entire depth and in retrieving the Shelby tubes of the hard brittle soil-cement resulted in a wide variation in the strength results, with peak shear strengths ranging from 500 psf to 5,000 psf.

Hayward Baker installed vanes in several columns and pulled them out of the columns after approximately 7 to 10 days of curing. A typical vane testing report is shown as Figure 14. The vane results indicated a column shear strength in excess of 10,000 psf.
The third method consisted of continuous SPT’s and visual logging of samples in completed columns. Figure 15 shows photos taken of samples of the soft clay collected before treatment and from a completed column showing the dramatic difference in the soil consistency. The SPT N-values also show a dramatic difference, as indicated on Figure 16. As indicated on the figure, the N-values before improvement are less than 5 and in many cases “weight of hammer” or “weight of rods” as described previously. In the completed columns, the N-values vary from Figure 14 about 25 to more than 100.
Figures 17 and 18 show photos taken following completion of construction at each of the sites.
**Summary**

Numerous slope failures occur along Tonawanda Creek. Saturation of the upper silty soil combined with loss of support for the stream bank caused by erosion create a condition where the thick deposit of soft clay cannot support the slope resulting in numerous stream bank failures. Two projects, one in Niagara County by the US Army Corps of Engineers and one in Erie County by the Erie County Department of Public Works utilized a technique common in Scandinavia called “dry mixing” to remediate slope failures that affected Tonawanda Creek Road. The process involves mixing dry cement with the soft clay to form soil-cement columns. The results show that mixing the equivalent of 8 to 10 bags of dry cement with the soft clay in a hole that is 30 inches in diameter and 30 feet deep, results in a soil cement column that is 10 to 20 times stronger than the in-situ clay. The stronger, stiffer soil-cement columns support the road embankment and alleviate instability of the creek bank.

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