

Canadian
Geotechnical
Society



International
Association of
Hydrogeologists



58th Canadian Geotechnical Conference 2005
Saskatoon, Saskatchewan, Canada
“Innovation, Education, Celebration”

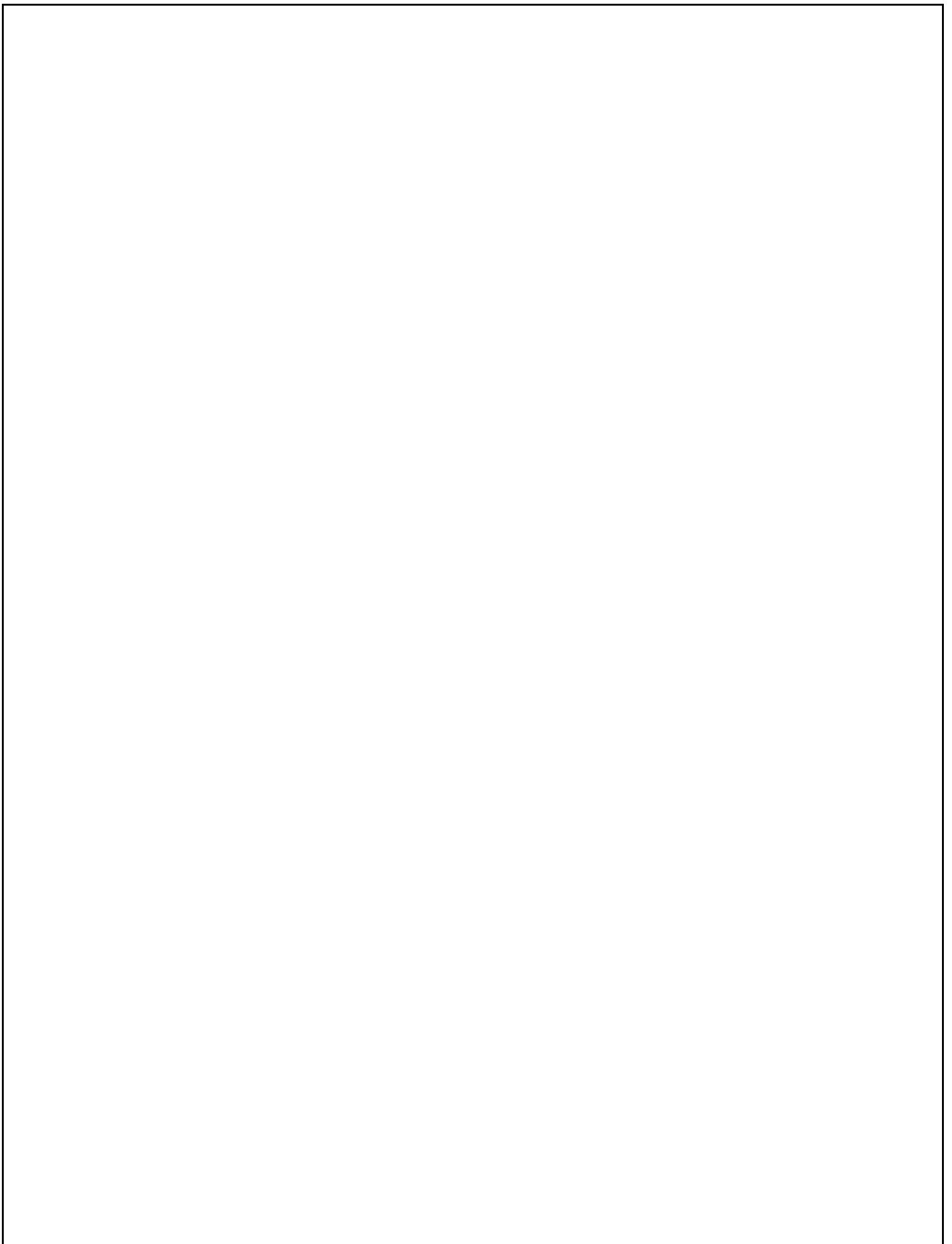
AN INNOVATIVE SLOPE STABILIZATION SYSTEM: SOIL NAIL AND ROOT TECHNOLOGY (SNART)

Mike Fabius, DST Consulting Engineers Inc., Thunder Bay, Ontario
Gord Maki, DST Consulting Engineers Inc., Thunder Bay, Ontario
Scott Tozer, DST Technologies Inc., Thunder Bay, Ontario

Compliments of:



DST Consulting Engineers Inc.
Thunder Bay, Ontario, Canada
1-800-668-4201
www.dstgroup.com



AN INNOVATIVE SLOPE STABILIZATION SYSTEM: SOIL NAIL AND ROOT TECHNOLOGY (SNART)

Mike Fabius, DST Consulting Engineers Inc., Thunder Bay, Ontario
Gord Maki, DST Consulting Engineers Inc., Thunder Bay, Ontario
Scott Tozer, DST Technologies Inc., Thunder Bay, Ontario

ABSTRACT

An alternative to retaining walls has been developed using soil nails without the need for drilling, grouting or shotcrete. This innovative system integrates various lengths of steel bar and root reinforcement aligned across failure surfaces. The nails are installed to depths of up to 30 m using small slope mounted equipment. This system has been used successfully to stabilize several 12 to 30 m high slopes in Canada. This paper reviews in detail the stabilization of 5 urban sites along a 30 m high riverbank in Ontario. The design consists of 38 mm steel bars up to 12 m long with heads, placed at a grid spacing of 1 to 2 m. The biotechnical facing consists of grasses and deeper rooted plantings. The owner and regulatory agency found that the system integrated well with their hazard management approach of attending to areas only when the crest encroached within a predetermined distance of a street or house.

RÉSUMÉ

Une méthode alternative aux murs de rétention a été développée avec l'utilisation de clous en sol sans le besoin de perçage, jointolement ou revêtement de béton. Ce système innovateur intègre plusieurs barres d'acier et de renforcement de racines, de longueurs variées, alignés à travers les surfaces affaiblies. Les clous sont installés, à des profondeurs allant jusqu'à 30 m, à l'aide d'équipement monté pour petite pente. Au Canada, ce système fut utilisé avec succès pour stabiliser plusieurs pentes variant entre 12 et 30 m de haut. Ce document réexamine en détail la stabilisation de 5 sites urbains le long d'une berge de 30 m de haut situés en Ontario. La conception consiste en barres d'acier de 38 mm et d'une longueur allant jusqu'à 12 m avec tête, placées en quadrillage de 1 à 2 m. Le revêtement biotechnique consiste d'herbes et de plantes à racines profondes. Le propriétaire et l'agence régulatrice ont trouvé que le système s'intégrait bien avec leur approche de la gestion du risque, soit de s'occuper des secteurs seulement lorsque la crête empiétait sur un terrain, à une distance pré-déterminer d'une rue ou d'une maison.

1. INTRODUCTION

This paper presents a new concept for stabilizing slopes up to 45° by integrating various lengths of roots and steel bars installed across potential failure surfaces. The system has been developed and has performed successfully in several case studies over 5 years.

In many cases, a soil slope that is oversteepened and unstable can be stabilized inexpensively by simply regrading the slope to less than the angle of repose, whether by cutting, filling or both. However there are often many site constraints preventing such a simple solution. Examples are a river at the toe, environmental permitting requirements, impossible access to the toe, buildings and infrastructure at the crest, or trees on the slope that must not be disturbed (Figure 1).

Unfortunately, the next simplest solution is a retaining wall either at the top or bottom, which is often the most costly, especially when considering shoring for installation and crane access. In addition, retaining wall construction can be disruptive to the environment and to neighbours.

As an alternative to conventional retaining wall systems, mechanically stabilized earth (MSE) is often considered. It's very economical, consisting simply of fabric or other reinforcing sandwiched within the slope. It is best suited for new construction (like an embankment) so that the reinforcing layers can be incorporated with the

construction. It is not so simple or economical if it means digging up an existing slope already unstable, given the necessary shoring and disruption. MSE systems effectively provide internal stability to a constructed earth embankment founded on competent foundation soils, but tend to fall short where weak foundation soils lead to stability issues in terms of global stability, or compound failure modes.



Figure 1: Kaministiquia River slope.

In order to develop a new solution, it is necessary to understand the potential slide mechanisms involved. The

trigger mechanism can include seismic loads, a rising water table (usually resulting in deep slides) or loss of soil suction (usually shallow slides). Seismic loading requires an understanding of the probability of occurrence and an understanding of the soil response (e.g. liquefaction). A rising water table requires judgment for selecting the highest likely water table no matter how much monitoring data is available. The loss of soil suction in particular can be difficult to engineer, although in the last few years many research projects and case studies have unearthed the failure mechanisms involved (e.g. Fredlund and Rahardjo, 1993).

An owner's requirements for stabilizing oversteepened slopes often include the following:

- low cost
- surgical application to localized problem areas,
- installed from the slope without affecting land use at the toe or crest during construction,
- engineered solution under complex slope geometry, groundwater and soil conditions,
- minimal impact on existing vegetation, and
- immediate risk reduction measure that can be improved upon at a later date.

A simple and practical solution that meets these requirements was developed in the late 1990's in Canada (Tozer and Fabius, 2000). It combines 3 existing and proven technologies, namely soil nails, biotechnical stabilization and laterally loaded piles.

2. INTEGRATING AVAILABLE TECHNOLOGIES

The key to the solution was found to be soil nails. However, the traditional shotcrete facing was determined unacceptable, too costly and susceptible to frost action. Roots proved to be a better facing solution, similar to nail reinforcement but shorter and at a much closer spacing, and very effective for arresting slips between nails.

The traditional drilling and grouting of nails was also unacceptable, again too costly. Instead, 3 alternate insertion methods were developed depending on soil type and condition: percussion (pile driving analogy), vibration (vibroflotation analogy) and rotation (auger analogy). The emphasis was on 'green' methods, minimizing disturbance.

In addition, the need for tension capacity in the nails was eliminated. Rather, lateral soil nail resistance was applied. This requires unconventional analytical techniques similar to laterally loaded piles as well as adding the concept of local shear in bearing, and modeling the soil flowing around a narrow rigid member.

It was found that the design of this system was much more sensitive to the soil strength parameters (ϕ and c') than most geotechnical design work. An overly conservative friction angle results in a considerably higher cost. For example, a 2 degree increase in ϕ can result in a 20% savings in the total lineal quantity of nails.

Therefore the cost of detailed geotechnical work is easily recovered.

The development of the system as it stands today was not a sudden 'breakthrough' idea. Instead it was an incremental response to highly motivated customers aggressively pushing engineers and constructors to provide a cost effective solution to slope problems having numerous constraints, one that could be installed quickly with minimal disruption to local services, the environment and neighboring land owners. The development of SMART can be illustrated with 3 selected case studies, the last of which is discussed in detail in this paper.

3. OF SUN KINKS, SHORT NAILS AND GLUE

In Case 1, a railway needed a solution to stabilize a 12 m high embankment where excavation for a culvert repair at the toe had loosened and oversteepened the slope. In a wide curve, the result was a loss of the shoulder and lateral tie support, causing a sun kink (when the rails expand in the summer heat and shift sideways to the outside of the curve). Construction access for slope flattening in the remote northern Ontario location was not an option. Being a granular embankment, the sliding mechanism was known to be shallow. The concept of pushing a few steel bars into the slope as reinforcement was tested, but the failure mode involving shallow sloughing between the nails could not be rationalized, even with a grass root facing. The idea of a plate at the surface of the nail, similar to a nail head, was developed but found difficult to model and analyze.



Figure 2: Railway embankment stabilization

A full scale test was set up. A 38 mm diameter steel bar was fixed to the bottom of a large box of sand, and the box lifted to model the sliding soil. A 'head' oriented perpendicular to the slope was added and instrumented since no suitable mathematical model could be found to predict the resistance of a fixed body against flowing sand. The slope was successfully stabilized with short 2 to 3 m nails with 'heads', integrated with a grass root facing. As a further precaution to prevent sun kinks, epoxy (a technology developed for high speed rail to prevent stone ballast from becoming airborne) was applied along the shoulder, essentially gluing the stones

together for extra lateral support. The SNART solution was successful.

4. OF WINE, LONG NAILS AND SPIDERS

In Case 2, a railway had a problem with a 16 m high sidehill fill in the Niagara wine region of Ontario. Weak clay materials meant that the slope was periodically creeping downhill, causing excessive maintenance costs and concerns. Constraints consisted of avoiding restrictions to rail traffic at the top during construction, avoiding environmental impacts on the creek at the toe and avoiding access to the site through the adjacent vineyards. Again, the soil nail approach was developed to pin the fill across the slide zone, while also applying the nail heads. To increase shoulder width, a steel retainer strip was added along the shoulder, welded to the nails. Furthermore, a method of installing 38 mm bars to 8 m depths was developed using a percussive hammer mounted on a small spider-like excavator capable of walking on steep slopes up to 45°. The SNART system was monitored after construction, and proved successful.



Figure 3: Kaministiquia River, Thunder Bay

5. OF RIVERS, 75 YEAR NAILS AND THE CZA

Case 3 developed when an owner tendered out the design-build of a stabilization system for 5 localized areas along a 30 m high regressing river bank in an urban area (Figure 3). The owner was managing the hazards innovatively with the Cautionary Zone Approach or CZA (Fabius et al, 2004) whereby areas are stabilized only when the crest has regressed to within a pre-set distance from the house or street. Trials with 38 and 50 mm nails confirmed that these could be installed to 25 m depths

with equipment working on the slope. The 75-year design criteria was achieved with a sacrificial allowance for corrosion, and the system was optimized with several different nail lengths and 3 types of facings, 2 of them biotechnical. This system proved the best solution with respect to cost, environmental impact, construction disruption and surgically repairing localized areas only.

6. THE SNART CONCEPT

Unlike conventional nailed walls the system does not rely on tension capacity of the nails. Instead the design is based on lateral resistance provided by the reinforcement across potential slide surfaces. The nails reach past all slide surfaces not having the target degree of safety. Typically the shallower the potential slide, the higher the nail density is needed to achieve the design safety factor. For very shallow slips, typically less than 1 m, the nail spacing would have to be too dense to achieve the objective of an economical system. Instead, the resistance is achieved with special transverse heads on the nails and a dense root facing. The vegetation also reduces infiltration, increasing soil suction and strength.

This system is typically applicable to steep slopes of up to 45° and incorporates 30 to 60 mm diameter steel bars at a spacing of 1 to 2 m with roots designed for 150 to 500 mm of penetration. Specific construction issues that have been resolved for the SNART system are installation methods, splicing methods and providing temporary soil resistance until the roots have reached design depth.

Although SNART is a permanent solution to stabilize a slope, some movement must be realized in order to mobilize the resistance through soil-nail interaction. Based on monitoring as well as analytical models, this movement is generally less than 10 mm. Deformation can be reduced with additional nails for a stiffer system.

The SNART system is very adaptable. If the slope does not merit comprehensive geotechnical investigations, conservative input assumptions can be applied, knowing that if excessive movements are noticed it is relatively simple to add more nails.

7. CASE 3: DETAILED DISCUSSION

7.1 Background

This site has been described in detail by Fabius and Suke (1990). The Kaministiquia River meanders through deep alluvium on the way to its delta on Lake Superior. The unstable area comprises a 2 km stretch of steep 30 m high riverbank in Thunder Bay, Ontario (Figure 3). Slope angles vary from 27° to 45° to the horizontal. Slope failures observed in the past have always been shallow, and occur after river floods (undercutting by river erosion) and after rainfall or during spring thawing (loss of shallow soil suction) causing regression at a rate averaging 0.5 m/year. This natural process of erosion at the toe results

in an oversteepened slope which periodically fails and slides into the river.

In 1984 the toe erosion was arrested with a rip rap revetment placed along the toe of the riverbank. The slope was then allowed to gradually flatten to 24°. This meant that eventually the street and several houses would be lost. A 350 m length of street in imminent danger was stabilized at that time with a costly anchored soldier pile retaining wall at the top of the slope.

Hazards for the remainder of the slope were managed with the CZA or Cautionary Zone Approach (Fabius et al, 2004a), with 6 and 10 m wide cautionary zones established for the street and houses, respectively (Figure 4). This was feasible because of the ability to accurately predict the maximum slide depth at this site. The CZA was found to be a practical and economical way to manage the hazards and risks in a prioritized, diligent and acceptably safe way. Stabilization measures are only applied to localized areas when the slope crest encroaches on the cautionary zone, meaning that stabilization costs are deferred for decades. Remedial action is required when the crest encroaches on the cautionary zone. The width of the cautionary zone can be varied with the desired degree of risk to be applied. Until the crest regresses to the cautionary zone the facilities are unlikely to be affected by a slope failure.

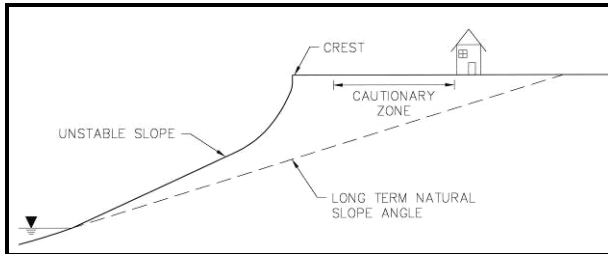


Figure 4: The Cautionary Zone Approach (CZA)

When the street's 6 m cautionary zone was recently encroached at 5 locations (Figure 5), the City and the Lakehead Region Conservation Authority tendered out a design-build solution. Design criteria included a factor of safety of 1.3, minimal construction disturbance, minimal maintenance costs and a 75 year design life. The successful tender was a soil nail and root technology solution.

7.2 Subsurface Conditions.

The slope is predominantly non-plastic silt extending well below river level. There is a 3 m thick sand layer at the top, and below that in some areas an upper deposit of firm clay with sand seams and multiple perched water tables. The main water table is 20 m deep (Figure 6).

Boreholes at the top of the slope indicated a soil that was lightly overconsolidated. However given that the slope has been created through erosion by the river at the toe, it was expected that the degree of overconsolidation would increase down-slope. This meant that within the

stress range of typical slide surfaces, the angle of internal friction would increase as well. Additional samples were subsequently obtained and the higher ϕ' confirmed with a few direct shear tests (Figure 7).

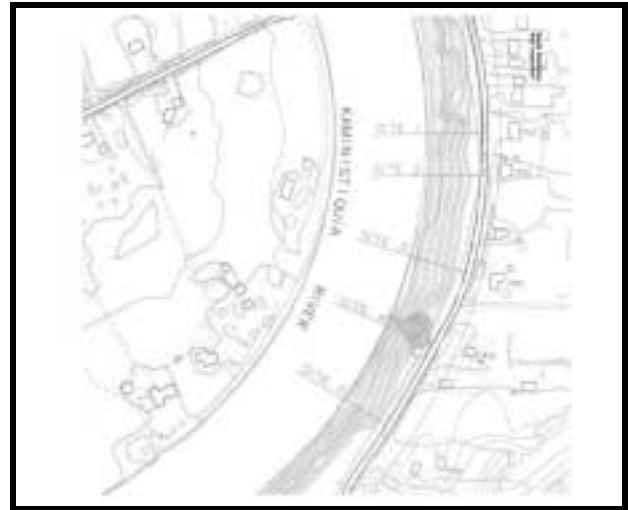


Figure 5: Five areas requiring stabilization

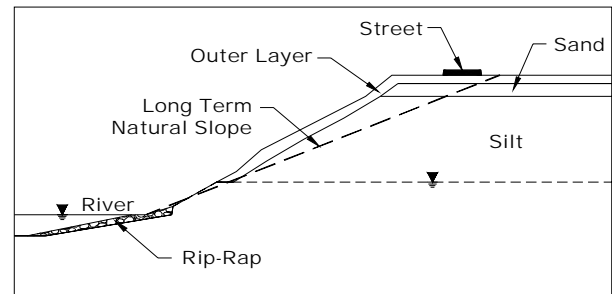


Figure 6: Subsurface conditions

Normally consolidated strengths were selected for the soils located behind the crest, with ϕ' of 30°. Overconsolidated soil parameters with ϕ' of 34° were assigned to the slope in front of the crest. Within 2 m of the slope surface, the soil strength was modeled as normally consolidated because of potential frost action and saturation.

7.3 The Design

For the five areas where the crest has regressed to within 6 m of the edge of the road, the overall slope angle varies from 25 to 30°. The height of slope, from crest to river level is 30 m, of which 5 m is below river level.

7.3.1 Slope Stability

Three modes of failure were analyzed for this slope: wedge, rotational and translational slides. Of these, rotational failures were found to control the soil nail design and spacing for deep-seated failures (typically at depths of 3 to 10 m). The translational slides control the

shallow soil nail spacing, head requirements and facing requirements. Three dimensional analyses were applied to small failures between the nails.

Rotational slip surfaces were analyzed using Slope/W (by Geoslope) and the Morgenstern Price method. To find reinforcement zone where failure surfaces have a degree of safety less than the target safety factor). This typically varies from 8 to 11 m deep at the 5 sites.

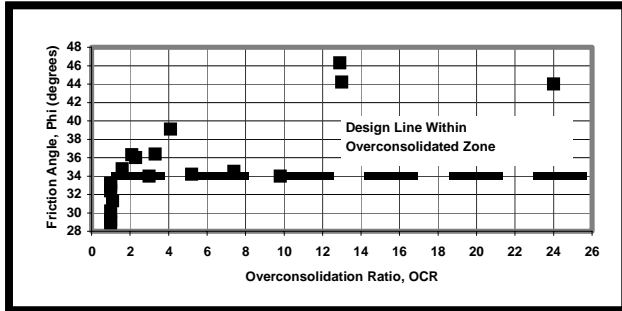


Figure 7: Consolidated direct shear test results with OCR

7.3.2 Nail Design

The design of the nail itself is based on the bending moment and shear resistance. Analyses found that the design was controlled by the maximum allowable bending moment.

Soil nails are subject to corrosion over their design life. The general approach for dealing with corrosion is to classify the soil conditions with respect to corrosion potential, and design for those conditions either with a protective material (e.g. grout and/or plastic sheath), a zinc coating or a sacrificial allowance of steel. The latter is often used for non-aggressive soil environments.

In the case of traditional soil nail systems the nails are used for near vertical slopes, and the design relies primarily on tension capacity. Nails in tension are highly susceptible to significant losses in capacity from stress concentrations caused by localized corrosion such as pitting. The SMART system, on the other hand, relies on bending and shear of the steel and do not have this weakness.

It is also of note that unlike an anchor or nail system designed in tension, the success of the system does not hinge on any individual steel bar. Furthermore, in order for multiple corroded bars to affect the system, all corrosion failures would need to occur along the same soil slip surface, which is highly improbable.

The sacrificial approach was applied for long term performance. The allowance was determined based on actual corrosion of steel plates buried in the ground for many years (Murray, 1982). This approach ranks corrosiveness based on several factors and determined that a 1 mm maximum sacrificial thickness for the steel surface (2 mm over the nail diameter) was required. The

bars selected were 38 mm diameter concrete reinforcing bar.

Three splice methods were developed and included butt welding, sleeving, and a simple welded overlap of the steel bars. The welded lap splice proved to be the most efficient, and was designed to meet the 75 year design life requirement as well as installation stresses. Splices were required at 5 m intervals, and rapid welding techniques were developed.

7.3.3 Nail-Soil Interaction

Analyses of nail-soil interaction were carried out in accordance with traditional bearing capacity theory (local shear by Vesic, 1963) as well as utilizing the general approach for soil nails outlined by USDOT (1994). In addition, an analysis of performance was carried out utilizing a soil structure interaction analyses program for laterally loaded piles and shafts.

With the local bearing capacity of the soil along the bar and the moment capacity of the nail, static analyses were first carried out to determine nail resistances. The first case (Figure 8) assumes that the nail is held rigidly below the slip surface and the available nail resistance is limited by the length of nail provided above the slip surface. At ultimate failure, the nails remain embedded within the slope as the soil mass flows around the nail. The nail head was also modeled for additional resistance against shallow slides.

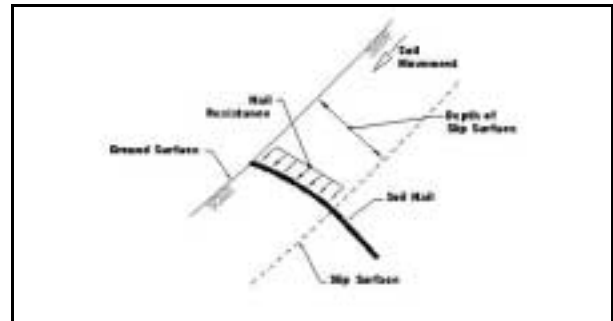


Figure 8. Soil resisted by nail above slide plane

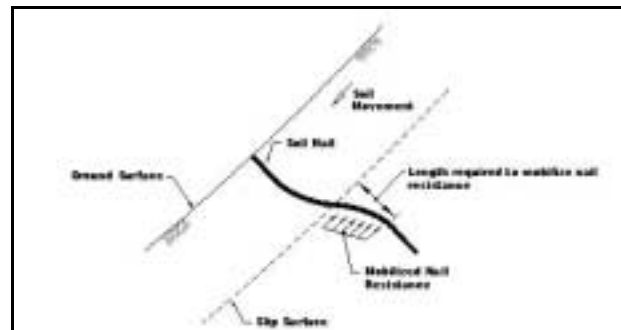


Figure 9. Soil resisted by nail below slide surface

The second case (Figure 9) assumes that the depth of the slip surface is sufficient to fix the upper portion of the nail within sliding mass. In this case, the length of the nail available to mobilize resistance is a function of the moment capacity of the nail. The minimum length of nail required below the slip plane to mobilize this resistance is assessed. The available soil nail resistance is a function of the critical mode of interaction, nail properties, soil properties and confining stress or depth. As such, the available resistance provided by the nail varies significantly throughout the slope (Figure 10).

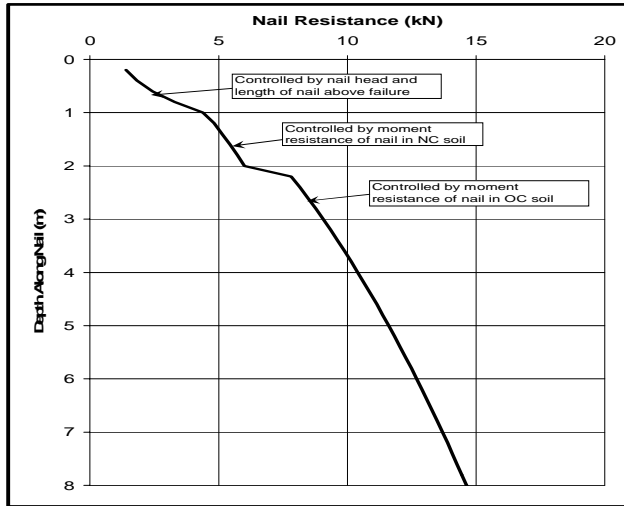


Figure 10. Nail resistance with depth

An assessment of lateral deflections required to mobilize the soil nail resistance was carried out utilizing LPILE Plus 3.0 software by Ensoft. The nail resistances determined were close to and slightly higher than that calculated with the bearing capacity method. Lateral deflections required were calculated between 5 and 20 mm within the upper 1 m of the slope surface, 3 to 5 mm within a depth of 1 to 2 m, and less than 3 mm below a depth of 2 m. These are conservative, since with a slope safety factor greater than one the full resistance is never actually developed.

The deflection analysis also confirmed that the length of bar required to mobilize the full soil nail resistance varies from 1 m near the slope surface to less than 0.3 m at a depth of 10 m. This value determined the depth below the critical slip plane that the nails needed to penetrate. LPILE analyses were also carried out to limit the size of the nail head to ensure potential loads on the head did not exceed the moment capacity of the nail.

7.3.4 Soil Nail Lengths

The distribution of soil nails with depth was optimized through a comparison of the resistance at various depths required to achieve the desired safety factor, with the nail resistance available as determined through nail-soil interaction analyses. The density of nails required decreases with depth.

Table 1. Nail distribution on face, Site 5.

Layer #	Elevation (m)	Slope Angle	Nail Distribution m ² /nail		
			3m length	4.4m length	11m length
1	183.5 – 195.0	27.6	1.5		3
2	195.0 – 200.0	23.5	1.5		3
3	200.0 – 208.0	33.7	0.75	3	3

The nail distribution was initially established based on the higher nail density requirements for slip surfaces near the slope surface, which vary with slope angle on that portion of slope. The length was then adjusted to meet the reduced nail density requirements at depth. The nail density and length requirements for Site 5 are shown on Table 1 and in Figures 11 and 12.

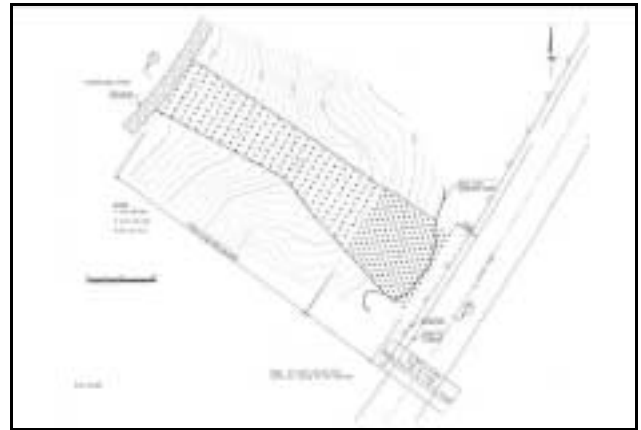


Figure 11: Nail layout for Site 5

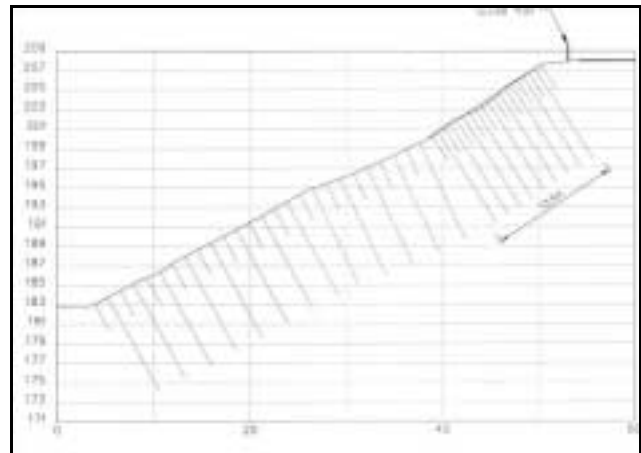


Figure 12: Section through Site 5

The optimal nail layout on the slope was a diamond pattern, with each horizontal row offset from the adjacent one.

7.3.5 Facing Design

The soils at this site are non-cohesive, and prone to shallow sloughing at slope angles approaching or exceeding the angle of internal friction of the soil at times of no soil suction, i.e. when they lose all their moisture or when they saturate during prolonged rainfall. Under these conditions, soils nails alone are not a cost effective means of improving stability for shallow failures. The depth and stability for these shallow sloughs are influenced by the nail/head spacing, saturated soil strength and the slope angle. For this project additional strengthening is required to depths of 0.3 m, with a few localized steep areas of up to 0.45 m, to improve the stability of soil between soil nails and heads. The maximum required root cohesion and depth in each layer for the biotechnical facing are illustrated in Table 2.

Table 2. Root strength and depth required, Site 5.

Layer #	Elevation (m)	Slope Angle	Nail Spacing (m)	Root Cohesion	Root Depth (m)
1	183 – 195	27.6°	1x1.5	0.1 kPa	0.1
2	195 – 200	23.5°	1x1.5	0 kPa	0.0
3	200 – 208	33.7°	1x0.75	0.7 kPa	0.5

An alternate facing method involves the placement of a higher strength material, such as rockfill, to the required depth, and this was used in 2 localized areas to fill zones where past slides had left a near vertical scarp. It was found that the angle of internal friction of the fill material needed to be at least 8 degrees higher than the angle of the slope surface (for slopes no steeper than 34°) in order to achieve a strength equivalent to the design cohesion.



Figure 13: The design grass for 350 mm roots

A local grass mix design was assessed (Figure 13). Several direct shear tests were carried out on a 70 mm diameter tube sample obtained from an area planted several years ago. The results are illustrated on Figure 14 (the cohesion is calculated from the difference in soil strengths with and without roots) and indicate that the grass will meet the design requirements for depths up to 350 mm. For the few areas where a steeper slope requires deeper reinforcement (up to 450 mm), the grass was supplemented with rooted hybrid poplar.

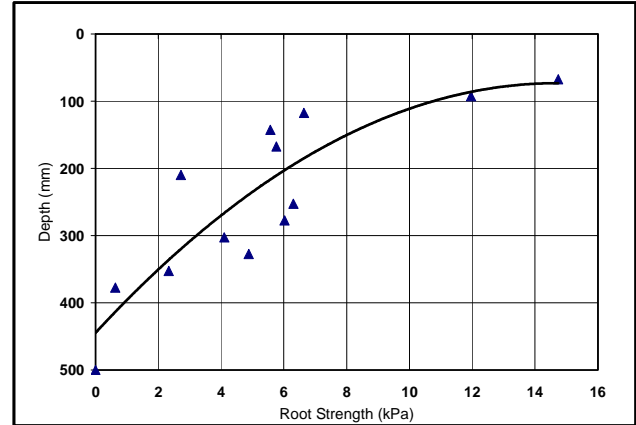


Figure 14: Test results of root strength with depth

The one thing about a biotechnical facing is that it does not provide instant strength like shotcrete. Therefore it is important to rely on shallow soil suction for several weeks or months until the roots are in place. An analysis of the effects of soil (matric) suction was carried out, indicating that at least 50 kPa of suction had to be maintained in the short term (Figure 15). The soil water characteristic curve (SWCC) was estimated for each soil type based on grain size and indicated that no more than 40% saturation could be accommodated to maintain this suction. This was considered reasonable for the normal level of moisture. Furthermore, in the event of saturation from severe and prolonged rainfall the expected sloughing would be localized and less than 0.5 m deep. In other words, easily repairable.

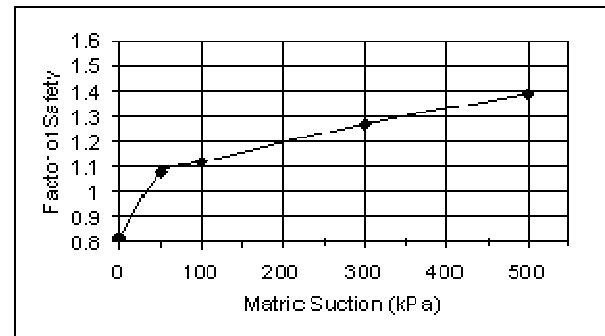


Figure 15: Effect of soil suction on stability

8. THE CONSTRUCTION

The soil nails were installed using small equipment working on the slope (Figure 16). This spider-like equipment has 4 legs (2 of which have wheels) and an excavator arm, and can work on slopes up to 45°. A percussion hammer was mounted on the arm. Minor grade adjustments were made where steep scarps remained. The 38 mm diameter steel bars were inserted in 5 m lengths using percussion methods. Lap splices

with welds were used. The nail heads were designed to terminate just below the slope surface.

During the work, a sliding pipe underground detector (SPUD) system was installed as a simple way to monitor the slope for any signs of impending instability. A SPUD is simply a plastic casing installed vertically into the ground at the crest. A short piece of pipe sliding inside the casing is designed to jam within the casing if its curvature exceeds the maximum deformation allowance selected. The pipe is left on the end of a string at the bottom of the casing. Pulling the pipe up a few times per day will warn the crew if unsafe movement has occurred.



Figure 16: Driving soil nails from slope.

9. CONCLUSIONS

An innovative soil nail system and root technology system has proven to be a cost effective alternative to retaining walls and MSE or mechanically stabilized earth walls. Over the past 5 years the system has been developed with new analytical techniques, light installation equipment, rapid splicing techniques, special nail heads and a biotechnical facing. The soil nail and root technology or SNART system borrows from and integrates 3 proven technologies: soil nail walls, shallow biotechnical stabilization and laterally loaded piles. A successful case study involving a 30 m high steep slope in an urban area has been discussed in detail in this paper. Design concepts have been developed that deal with the many possible modes of failure.

The SNART system was found to have the following features:

- The system is an economical long term engineered solution for oversteepened soil slopes up to 45°.
- The system can be surgically applied to specific problem areas.
- The technology is proven and reliable; installed systems have performed successfully for more than 5 years.
- The system can be installed with minimal disruption to vegetation and the slope in general.
- The nails are buried when installed, and with the biotechnical facing provide a natural look.
- The system can be installed using equipment operating on the slope, meaning very little disruption to local traffic and residents.
- The system installed on the Kam River does not impact the existing facilities, including the road, the watermain and the rip rap toe protection.
- The system can easily be expanded to new areas that require stabilization as natural slope regression occurs over future decades.
- The long term maintenance costs over the 75 year design life are essentially nil.

10. ACKNOWLEDGEMENTS

The authors thank DST Technologies Inc. for permission to publish this case study, and acknowledge DST Consulting Engineers Inc. for permission to publish details of their patented soil nail system. The opinions expressed in this paper are those of the authors and not necessarily those of either the Lakehead Region Conservation Authority or City of Thunder Bay.

11. REFERENCES

- Fabius, K, Fabius M., Vanapalli, S.K. & Garga, V.K., 2004. The investigation and stabilization of a high river bank in Thunder Bay. 58th Canadian Geotechnical Conference, Canada, Quebec.
- Fabius, K.A., Vanapalli, S.K., Garga, V.K. & Fabius, M. 2004a. Managing landslide hazards with the cautionary zone approach. IX International Symposium on Landslides, Rio de Janeiro, Brazil.
- Fabius, M., & Suke, S.M. 1990. The investigation and stabilization of a high river bank in Thunder Bay. 43rd Canadian Geotechnical Conference, Canada, Quebec, pp 69-75.
- Fredlund, D.G., and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley & Sons, New York.
- Murray, 1982; Assessment of Steels for Reinforced and Anchored Earth Structures, Contractor Report 288, by the Transport and Road Research Laboratory).
- Tozer, S.E. and Fabius, M. 2000. Steep nailed embankment technology: 2 case studies. 51st Annual Highway Geology Symposium, Seattle, USA.
- USDOT, United States Department of Transportation. 1994. Federal Highway Administration, Application Guide for Launched Soil Nails Volume 1.