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**STEEP NAILED EMBANKMENT TECHNOLOGY:
2 *SMART* CASE STUDIES**

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STEEP NAILED EMBANKMENT TECHNOLOGY: 2 SNART CASE STUDIES

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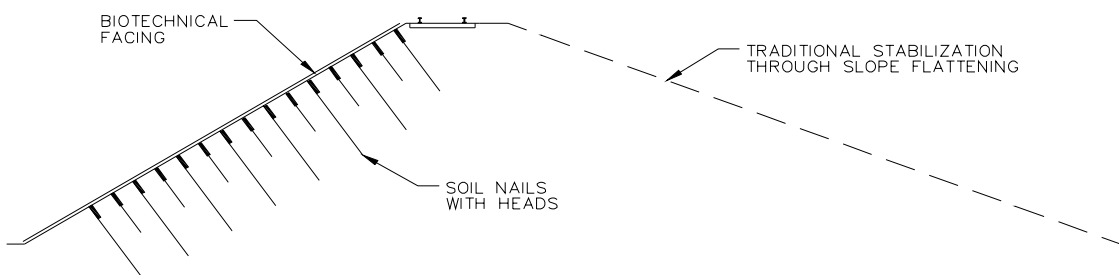
Abstract: This paper describes an innovative and economical method of stabilizing existing embankment slopes where there is insufficient right-of-way for flattening the slopes, where environmental impacts need to be avoided or where there are constraints to equipment and material access. This soil nail and root technology (SNART) draws from two well proven technologies, namely soil nailing and biotechnical stabilization.

The concept involves a slope reinforced with steel bars (nails) that are installed without drilling or grouting, together with a biotechnical facing. Design methods developed for the various failure modes, the results of full scale model studies and development of economical installation methods are described. Two case studies are reported on SNART as applied to railway embankments: (a) a 16 m high fill in cohesive materials and (b) an 11 m high fill in cohesionless soils. Performance measurements are presented and discussed for this proprietary technology.

Introduction

Fill embankments are an economical way of achieving grade changes for highways and railroad tracks over low areas. With the advent of geosynthetic reinforcing materials over the past few years, new embankments can be built with slopes much steeper than the traditional (typically 2 horizontal to 1 vertical) fill slopes required to achieve stability (for example, TRB, 1987 and Xanthakos, 1994). Steeper slopes mean less property requirements and less environmental impacts. Unfortunately, these methods are impractical for dealing with existing embankment slopes that need additional stability (often as a result of grade raises, widenings, erosion or heavier traffic loadings), given that the embankment would have to be dismantled to incorporate the geosynthetics. Where sufficient right of way is available, equipment access is simple and materials are available, slope flattening is often the most economical solution. Conventional methods available for stabilizing oversteepened slopes without flattening are very costly, requiring sheet piling, driven or bored piling or retaining walls (for example, Taylor and Voor, 1998)

Figure 1 – Typical solution for over steepened embankment



Given the above, there is a need for a solution that stabilizes oversteepened slopes economically. Such a system should ideally meet the following criteria: (a) a design basis using engineering analysis, (b) installation without affecting traffic on the embankment, (c) installation in areas with difficult access, (d) be of similar cost to conventional slope flattening/widening, (e) have minimum impact on the environment, (f) be aesthetically pleasing, and (g) have the ability to be monitored for performance. A new system has been developed at DST Technologies Inc. (a Canadian firm specializing in geo-solutions) that will meet these criteria. It combines 2

proven technologies, namely soil nailing (traditionally installed with a shotcrete facing on almost vertical cut slopes) and a biotechnical facing (traditionally used to stabilise slopes against surface erosion).

Traditional soil nails consist of steel bars inserted generally perpendicular to the slope, usually by drilling and grouting methods. The surface is covered with steel mesh and shotcrete is then applied to complete the stabilized cut. To meet the criteria for fill slopes, new installation methods had to be developed that avoided the costly drilling and grouting, and permit installation without requiring equipment at the top of the embankment. This involved field installation trials to develop. Furthermore a facing was required to replace the costly shotcrete facing while still stabilizing the shallow soils between the nails. This required large scale testing to establish analytical methods for shallow failure modes of soil slippage around nails.

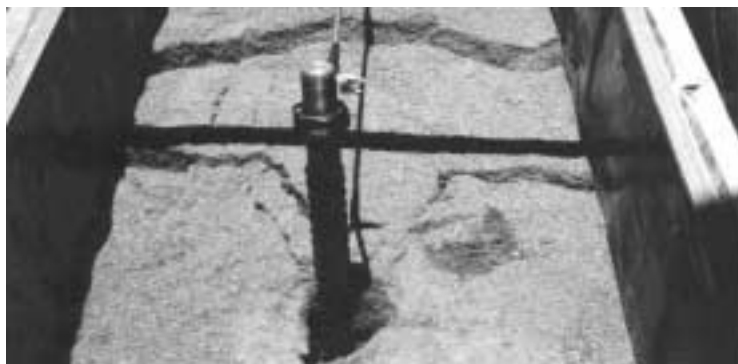
The Technology

The fundamental concept of SNART consists of reinforcing the soil using ‘passive’ closely spaced bars together with an engineered surficial facing comprising plant root reinforcement. Designs are site specific, and often require geotechnical data to optimize the design. With SNART, the nails are steel bars, typically 25 to 75 mm in diameter with lengths of 2 to 15 m, and are designed with an allowance for corrosion over their design life. Nails are typically spaced at 1 to 2 m, extending about 1 m into stable materials. This system requires small movements within the slope in order for the required resistance to be mobilized. A typical system is illustrated in Figure 1.

Soil nail technology is well developed for vertical slopes for temporary excavations, including design methods (for example, TRB, 1987 and FHWA, 1991). A shotcrete or precast concrete facing deals with shallow slip of near surface soils, while the deeper potential slip failures are stabilized with the lateral resistance of the nails across the slip plane. Fill slopes, on the other hand, are flatter, (less than 45 degrees) and do not require high strength facings such as shotcrete. Furthermore, in many instances a shotcrete facing is not suitable where frost action is a long term consideration.

Full scale model studies at DST’s laboratories have shown that a nail head detail is required to stabilize the slope against a failure mode whereby shallow cohesionless soils could flow around the embedded nails (Figure 2). New analytical methods therefore had to be developed to deal with this. As a result, various types of nail heads were investigated for working in association with a shallow root system over the slope surface. The optimum head was found to be a 200 x 200 mm shear plate welded near the top of the nail and oriented parallel to the slope (Figure 3). This was developed to achieve a minimum of 5 kN resistance per nail.

Figure 2 – Full scale model testing of shallow soil resistance around nail



Another way that embankment slopes are different than steep cut slopes is the need to maintain a stable shoulder. This is particularly important for railway embankments where the narrow shoulder provides lateral support to the ties. Shoulder stabilizations have been developed that integrate with SNART, including epoxy stabilization, precast tied and nailed concrete retainers and nailed retainer strips (Figure 4)

Figure 3 – Nail head detail

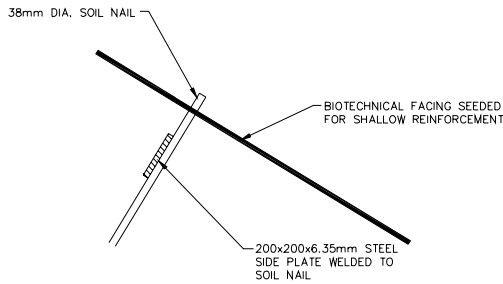
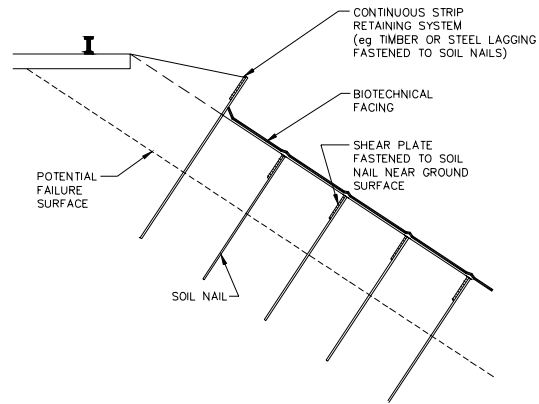


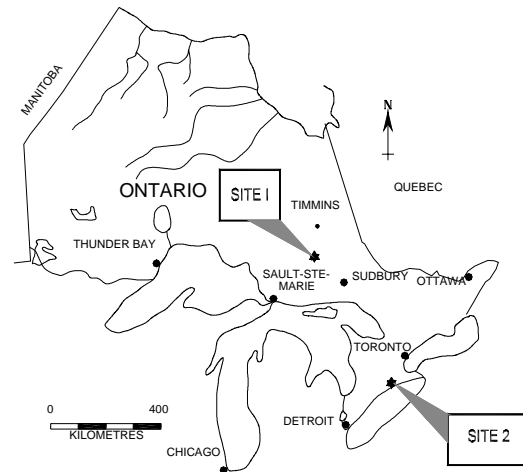
Figure 4 – Detail section of nailed retainer strip.



A biotechnical facing is an integral part of the system. This incorporates a layer of surficial roots that impart an effective cohesion to the soil properties (see, for example, Gray and Solir, 1996). Furthermore, the facing keeps the near surface soils moist, imparting a small additional cohesion which is known to extend deeper than the roots themselves. The facing is engineered with respect to root depth, depending on the site specific conditions.

Developing economical installation methods that do not affect train or highway traffic is an important hurdle in unlocking the power of this technology. To that end, methods were developed for installing the nails with equipment that could access the steep slopes (as steep as 45 degrees) and using percussive, vibratory and rotary methods. This eliminated the traditionally high drilling and grouting costs while providing a number of rapid and economical installation methods that could be selected to fit site specific soil conditions. The ability to monitor the installation resistance of the nail also proved to be a valuable tool to identify localized variations in the stratigraphy, allowing field adjustments during installations to optimize the design.

Figure 5 – Site locations.



The soil nail and root technology (SNART) described above is well illustrated with 2 case studies in Canada (Figure 5). These are both railway embankments, one an 11m high embankment of cohesionless soils located in northern Ontario, the other a 16 m high embankment in cohesive soils located in southern Ontario. In both cases, a solution was needed that reduced continuing maintenance costs and as well as the risk of serious impacts from slope failures. Installations were completed in 1999.

At the 2 sites described in this paper, the nails were installed using percussion equipment installed on a specialized excavator. This equipment is self propelled and capable of climbing and sitting on slopes as steep as 45 degrees while driving in the nails. An installation rate of 100 nails per day was not uncommon.

Background and Site Conditions

Site 1

This remote site is located on a Class 1 railroad in northwestern Ontario. Following a culvert failure and repair that involved cutting into the slope of an 11 m high embankment, the track required resurfacing and had problems with insufficient shoulder width. The slopes are as steep as 40 degrees to the horizontal. The subsequent geotechnical investigation concluded that internal embankment (dry sands and non-cohesive silts)

soils and foundation soils (stiff clay) were unlikely to present long term problems. However, to achieve stability of the oversteepened slopes, it was decided to stabilize the embankment.

The diagnosis of the problem was as follows:

- Difficulties maintaining shoulders due to lateral train forces and sun-kinks in tight curve with steep slopes.
- Very loose sides (both) as a result of culvert repair work.
- Very loose, steep sides as a result of previous bank widening (through dumping from the top) of shoulders on outside of curve.
- Loose embankment zones due to some soil loss into culvert prior to its repair.
- Low factor of safety against shallow slips (parallel to slope) due to steep incompletely vegetated slope.
- Problems were exhibited over about 50m of embankment, centred on the culvert.

To address the above, an objective was set to improve the stability by 20%. Site constraints for traditional slope flattening proved to be difficult: access to the toe of one side of the embankment was difficult, there were no nearby fill materials, and the signals pole line would have to be relocated. After receiving bids for alternative solutions, DST's steep nailed soil technology was selected in conjunction with an epoxy stabilized shoulder to resolve the problem.

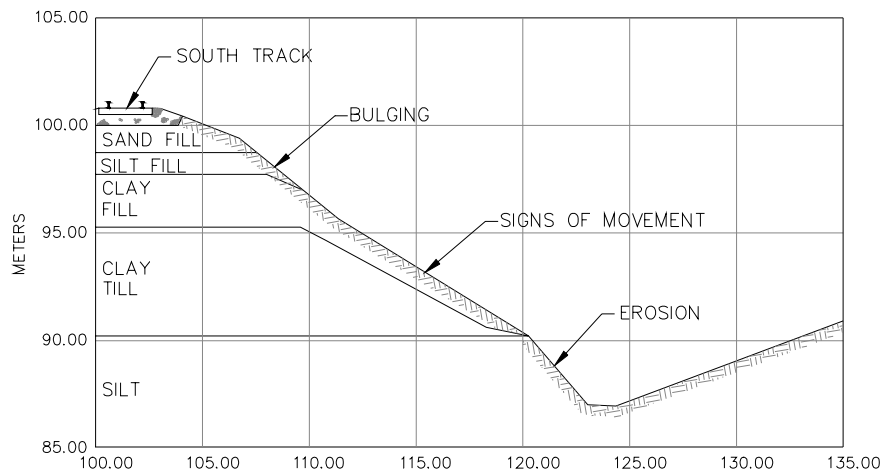
Site 2

This 30 m long slope instability is located on the south side of a double track railway embankment on a Class 1 railroad near St. Catharines in southern Ontario where double tracks cross a 360 wide creek valley on an embankment up to 20 m in height. In the location of the problem, the embankment is a side-hill fill. The slope is as steep as 43 degrees to the horizontal.

The south track was undergoing continued settlement and lateral shift (several centimetres a week) over about a 30m length of the track, close to the west end portion of the crossing. In the area, the embankment is 12 to 16 m in height. The settlement resulted in continuing maintenance of the south track and a slow order had been issued for all rail traffic.

A geotechnical investigation identified essentially stiff clay materials, with some non-cohesive materials above (Figure 6). The geotechnical report identified potential failure planes, both shallow and deep, and concluded that a) the south embankment slope was in borderline stability and b) that further movements could be expected to occur. Furthermore, the toe of the south embankment had signs of active erosion from runoff along the gully at the toe, and could be contributing to the problem. The preliminary design concept involved piling for stabilizing potential upper level shallow slides and slope flattening for the deep slide case.

Figure 6 – Subsurface conditions, Site 2



To address the above, an objective was set to increase the stability at shallow depth with a 20% degree of improvement combined with control of future erosion at the toe. After assessing costs for the conventional solutions, DST's steep nailed embankment technology was selected. This solution also had the advantage of requiring no environmental approvals (as required for slope flattening), conserving the existing trees on the slope and would have no impact on train traffic since installation equipment could work from the slope itself.

Results of Analysis

In order to design a SNART system, it is necessary to establish design criteria and check the design against all possible failure modes. The following design criteria were established for the 2 sites:

1. installation method to avoid disturbance of a buried fibre optic cable and pole line/signals,
2. installation method to avoid any impact on train traffic,
3. thirty year design life,
4. 20% improvement in safety factor against failure for both shallow transitional slips and deeper wedge or circular slips, and
5. shoulders stabilized without embankment widening to an equivalent standard section for railroad embankment shoulders, also adequate for support of construction traffic.

For the steep nailed embankment technology, the following failure modes need to be analysed using various potential slip locations as well as various nail lengths, diameters and spacings.

1. rupture of the steel nail in shear
2. lateral bearing failure of soil against nail below a potential slip surface(both short rigid and long flexible modes)
3. lateral bearing failure of soil against nail above a slip surface
4. nail pull out
5. shallow soil slip between nails
6. deep seated failure through soils below the nail
7. surface erosion from surface run off

Based on the geotechnical site report (which utilizes information from boreholes through the embankment and from laboratory testing), soil parameters are selected and a subsurface model developed. This is checked with a back analysis to confirm that reasonable safety factors result, and then applied to find the critical failure modes and locations using routine computer analyses. For the 2 sites in question, the following conditions were established for design purposes.

Site 1

The embankment materials here are dry and granular with sand and gravel on the outside of a silt core. No deep seated sliding planes are expected to have occurred in the past.

The following parameters were selected for analysis:

- sand and gravel: friction angle of 40 degrees (based on laboratory direct shear tests). When moist and unsaturated, add an equivalent cohesion of 1 kPa.
- silt: friction angle of 35 degrees (based on laboratory direct shear tests). When moist and unsaturated, add an equivalent cohesion of 2 kPa.
- groundwater table: at or below the base of embankment

The analyses indicated that in order to achieve the design criteria, 3 m long 38 mm diameter nails with 200 mm x 200 mm shear plate heads were required at a rate of 6 nails per lineal metre of embankment slope. These were concentrated within the upper half of the slope due to the drier nature of the soils here and the increased effects of train vibrations here. The design root depth for the facing was 150 mm, and a seed mix together with a biodegradable coconut fibre mat was specified for areas where existing vegetation did not meet this requirement. A total of 560 nails were installed (Figures 7, 8, 10)

To provide a stable shoulder, an epoxy ballast stabilisation treatment was applied. Epoxy glue was applied over the existing shoulder surface extending outward to the embankment crest with a pressurised spray operation. This product penetrates and cements the loose ballast while allowing it to drain freely and remain in place, reducing potential lateral movements of the ties (Figure 9).

Figure 7 – Site 1 Plan view

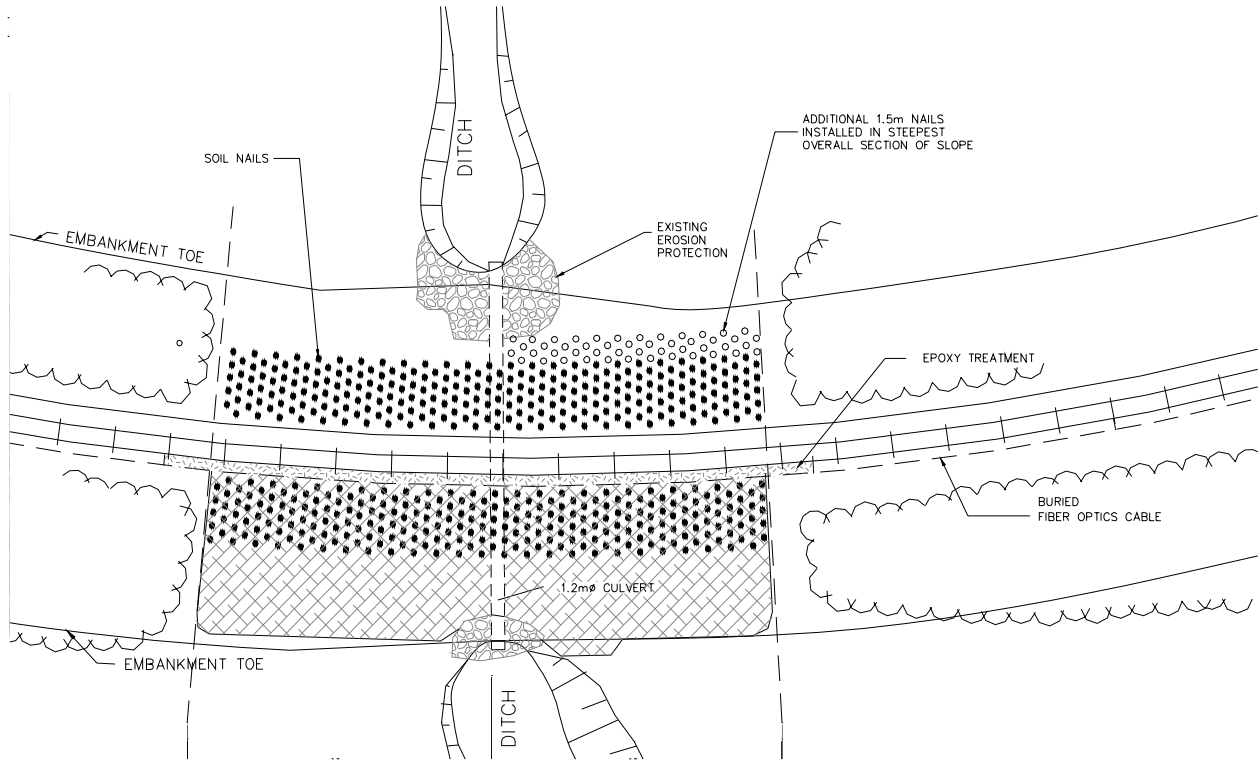
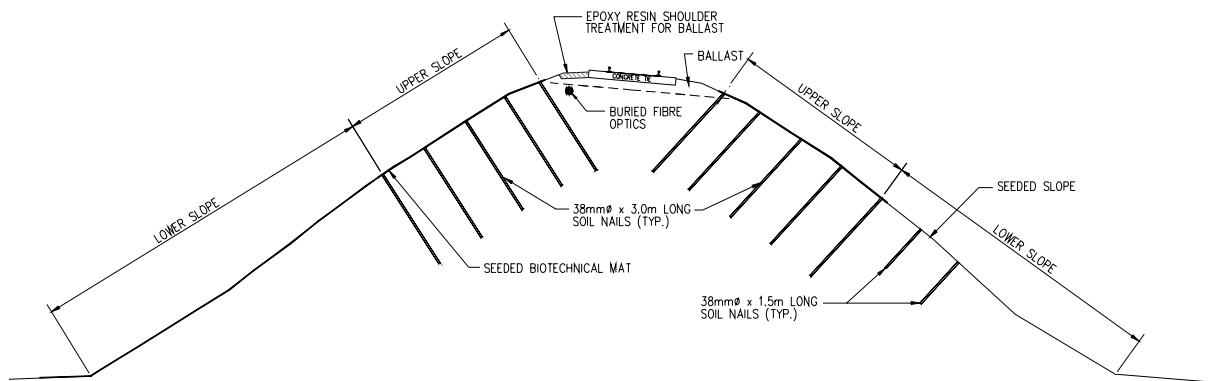


Figure 10 – Site I, Stabilized Embankment Section



Site 2

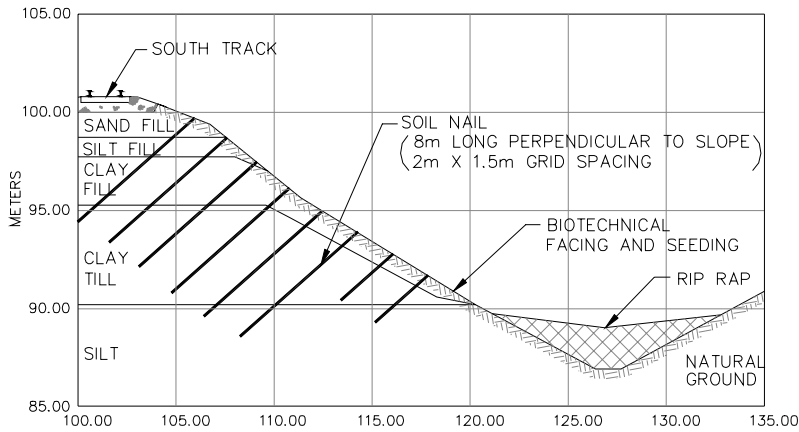
Based on the geotechnical report for this site, the embankment materials consist of silt and clay fills to a depth of 4.6 m below base of rail. These overly a stiff clay till which overlies a deep deposit of firm to very stiff clay below 9 m. On the slope a layer of sandy materials also overly the clay fill materials. Given the general topography, this embankment is a side-hill fill on ground that slopes to the southeast.

The following soil parameters were selected:

- Cohesive soils - effective stress parameters: drained angles of internal friction of 27 degrees (fill), 28 deg. (clay) and 35 deg. (till), with a cohesion of nil.

- Cohesive soils - total stress parameters: undrained shear strength of 25 kPa (clay) and 50 kPa (till).
- Cohesionless soils, a drained angle of internal friction of 28 deg. (silt till) to 31 deg. (sand fill).

Figure 11 – Site 2, stabilized embankment section.



Limit equilibrium analyses were carried out for slip surfaces passing through a weak zone within the clay fill at depths ranging from 2.6 to 4.6m below the top of the embankment. This mode of failure is referred to as “shallow slide”. As well limit equilibrium analyses were carried out for slip surfaces passing through the firm grey clay layer from 9.2 to 10.7 m below the top of the embankment. This mode of failure is referred to the “deep slide”.

The analyses indicated that in order to achieve the design criteria, 2.5 to 8 m long 38 mm diameter nails with 200 mm x 200 mm shear plate heads were required at a rate of 8 nails per lineal metre of embankment slope. A total of 275 nails were installed. Following nail installation, a coconut fibre biotechnical facing blanket was installed in order to promote new vegetation growth and assist in preventing erosion of embankment materials. All embankment faces within the stabilization area were seeded and fertilized (Figure 11).

At Site 2, the gully erosion at the toe of the embankment also needed to be addressed to regain all or most of the eroded toe, while retarding future erosion. This was accomplished by partially infilling the gully with rip rap and regrading to form a ditch within the rip rap.

Figure 12 – Site 2, installation of soil nails east limit of stabilization.



Figure 13 – Completion of embankment stabilization, soil nails and erosion protection installed.



Nails were driven into the embankment to specified tolerances with a unique mobile hydraulic walking excavator. The walking mechanism which allows for access up steep embankments consists of two wide base low pressure tires and two extendable out-riggers, all of which articulate and can be positioned or moved independently. The installation equipment is equipped with an articulating hydraulic hammer adapted and modified for rapid driving of nails. Impact from the hammer can be controlled and adjusted depending on the soil conditions and can provide an energy of up to 1400 J (Figure14).

Figure 14 – Installation of soil nails east limit of Site 2 stabilization.



SNART Economics

Options for grade stabilization of these two sites were put out for construction costing for slope flattening/widening solutions versus soil nailing. In both cases SNART costs were similar to those of traditional bank widening and slope flattening, although SNART had the advantage of requiring no environmental approvals and no need to relocate poles and signals lines.

Typical costs, excluding mobilization, are in the range of \$15 to \$50 (US) per square metre of slope face. At Site 1, a typical slope in granular soil utilizing 3 m long nails with heads on a 1.2 m grid and including a biotechnical facing, the cost was \$23 per square metre of slope treated. For a case of deeper slip planes, such as Site 2 in cohesive materials utilizing nails typically 6 to 8 m long nails with heads on a 1.2 m grid and a biotechnical facing, the cost was \$40 per square metre of slope treated.

At both sites, the system was installed under a design-build contract, allowing fast-track construction at minimum risk to the owner.

Performance Monitoring

At both sites, the embankment was monitored for movements during the installation, and this confirmed that there was no measurable impact on the tracks.

After construction, some soil movement must take place to mobilize the added resistance provided by the nails. Accurately predicting the amount of straining required is complicated because of the several possible modes of failure and combinations of these modes, although it should be at a decreasing rate compared to pre-installation performance. Such movements (strains) are expected to be relatively small (less than 100 mm) near the slope surface and will stabilize as the soil nails become 'active'.

At Site 1, while no ongoing monitoring system is in place, railroad operations personnel have reported excellent performance with no ongoing movements or maintenance requirements (in spite of a long history of problems, maintenance and slow orders).

At Site 2, both the tracks and the nail heads were monitored for movements for several months following construction. These indicated movements of up to 50 mm on the slope (that is, the nail heads), which indicates that the nails were building up the resistance to slope movement. The monitoring also indicated essentially no movements for the tracks themselves. Railroad operations personnel reported that track maintenance over this section has been significantly reduced and all slow orders over this embankment have been removed.

Summary and Conclusions

A new engineered system for economical stabilization of existing embankments has been developed utilizing soil nails with a biotechnical facing. The nails incorporate special heads, and complementary techniques have been developed for stabilizing narrow shoulders at the crest.

Soil nail and root technology (SNART) has proved to be an economical method of stabilizing embankments that have slopes which are too steep or that are already slipping. SNART is particularly effective where traditional slope flattening is not practical, for example if there is insufficient right-of-way, if environmental impacts need to be avoided or if there are constraints to equipment and material access. In such cases SNART has proven to be a powerful tool that avoids the high costs associated with retaining systems and piling. The system brings together the proven technologies of soil nailing of excavation slopes and biotechnical slope stabilization, made possible with the development of new analytical methods and economical installation techniques that avoid drilling and grouting.

A research and development program as well as two case studies have revealed both advantages and drawbacks. The main drawback to the system is the difficulty with installing nails into fills containing boulders or frozen ground. Furthermore, the system needs to be designed on a site specific basis with knowledge of the geotechnical data.

On the other hand the advantages of SNART are considerable. The system basically requires little construction equipment/materials, is readily adaptable to different sites, is not restricted by difficult access, can be installed very quickly, is cost competitive with conventional bank widening or slope flattening, is much less costly than piling or retaining wall options, requires no digging or drilling, involves minimal ground disturbance and does not restrict traffic at the top of the embankment.

Acknowledgements

DST Technologies Inc. currently has a patent pending on the technology described herein. The authors wish to thank the firm for permission to publish results of their research and development work.

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