GEOTECHNICAL STUDY ON SLOPE STABILITY IN VICINITY OF RIVER VALLEY

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ABSTRACT

The prevailing factors governing existing slope stability of drainage valley are valley protection, soil composition, ground water and seepage, soil erosion, frost wedging, surcharges and vegetation. Potential slope failure may impose an adverse effect on the adjacent structures founded on top of banks by weakening subsoil conditions that may lead to structural failure and serious bank slippage. The paper examines the effect of factors generally considered in slope stability analysis, and determines the structural setback from the toe of bank away from the zone of (bank) potential failure. The stability of slope in two projects in relation to the potential zone of instability for structures is thoroughly examined. The stable slope factors, i.e., soil composition, underground water and inclined angle of the natural slope and gradient slope, together with applicable flow erosion of creek at toe of the bank, are especially discussed in conjunction with the guideline presented by local environmental agency.

RÉSUMÉ

Les facteurs régnants sur la stabilité existante de la pente de la vallée de drainage sont la protection de la vallée, la composition du soil, les eaux sousterraines et l`infiltration, l`érosion du sol, le gel, les surcharges et la végétation. L`écroulement potentiel de la pente peut causer un effet nuisible à la structure adjacente qui ce trouve au pied de la pente fondée sur l`affaiblissement du sous-sol qui peut mener à la défaillance de la structure et à l`éboulement de la pente. Le document examine l`effet des facteurs généralement considérés dans l`analyse de la stabilité de la pente et détermine le recul structural du pied de la pente qui fait parti de la zone d`échec potentiel. La stabilité de deux projets par rapport à la zone potentielle d`instabilitée pour les stuctures est complètement examinée. Les facteurs d`instabilité de la pente, c.-à-d., la composition du sol, l`eau souterraine et l`angle interne de la pente normale et de la pente de gradient, ainsi que l`érosion du crique au pied de la pente, est particulièrement discuté en même temps que la directive présentée par l`agence environmentale locale.

1. INTRODUCTION

Stability analyses of the slopes nearby a river/tributary are becoming extremely important in recent years with emphasis on environmental protection, due to increasing economic pressure for sustainable development and gradual land development. Slope failures or movements in banks along drainage valley, pond and steep slopes are very common with human activity and environmental change.

Bank stability is influenced by factors such as inherent shear strength of the bank mantel, its soil composition, hydrological impact and toe erosion by water action. The diversity of conditions determines the slope stability of structural elements on the bank and the bank itself. Stability analyses of soil banks depends on the complexity of the slope. Some progress has been made in developing techniques to minimize the risk of bank failure causing serious damage to the structures built on the bank.

Short-term and long-term stability of bank slopes is a major concern of the geotechnical engineer in designing. The total stress analysis is used to evaluate the short-term stability of a bank during or on completion of construction (Fang,1990). The total stress analysis method that uses *in-situ* undrained shear strength is still widely used because of its simplicity without selecting a pore pressure. Contrary to total stress analysis, the effective stress method is used for long-term stability analysis. The distribution of pore water pressure is a fundamental factor in defining effective stress.

2. FACTORS CONSIDERED IN SLOPE STABILITY ANALYSIS

2.1 Soil Properties

Soil properties are essential aspects in theoretical analysis or practical computer modeling of a natural valley slope stability study or an engineered project assessment. For determining the mechanical properties of soil, both *in-situ* and laboratory testing methods are used. Field investigations may be carried out by Standard Penetration Testing (SPT) or augmented by continuous Cone Penetration Testing (CPT). Samples retrieved from SPT might be used for further testing in the laboratory. The test results are recorded as the Standard Penetration Resistance (or ’N’ values) of the subsoil, and the laboratory tests include moisture content, Atterberg Limits and gradation testing.

For soft sensitive clay deposit, *in-situ* vane shear and remoulded vane shear tests are performed. The tests to determine the undrained shear strength of the cohesive soil, and the ratio of the values of the undisturbed and remoulded shear strengths reveal the sensitivity of the slope soil.

Samples are used for grain size analysis and soil type classification. Typical, two types of soil are commonly classified, e.g. cohesive soil (silty clay, silty clay till, etc.) and cohesionless soil (gravel, sand, silt, etc.). The composition of soil governs the stability of the bank.

2.2 Groundwater Conditions

The groundwater influence in slope stability analysis can be investigated by field work, consisting of the groundwater seepage encountered during site drilling, or installing standpipe piezometers in the boreholes to monitor the groundwater fluctuations.

In a critical case, the fluctuation of groundwater in the bank mantel may have a detrimental effect by triggering a landslide. Groundwater levels may vary under different climate conditions. Surface runoff from weather changes may have an impact on stream flow and toe erosion. Deforestation will impact the water level.

2.3 Slope Inclination

Slope inclination is a major concern of the geotechnical engineer in slope analysis. Slopes have been generally identified as safe if the inclination is at 1V:2.5H in cohesive soils (i.e., clay and tills), 1V:2H in cohesionless soils (i.e., sand and gravelly sand), and 1V:1.4H in shale bedrock (CVC , 1992). Its stability also depends on vegetation cover and rooting reinforcement, movement in history, groundwater, seepage, creek meander and toe erosion, etc.

2.4 Surcharge

Surcharge loads (house, buildings, traffic, retaining wall, earth fill, excavation, loading pattern on the bank etc.) impact on the slope stability. Soil mass under given loads will impose a stress condition on the bank that may seriously effect the stability of slope. The stress of surcharge load vs. strength of the slope itself should not exceed certain tolerable limits. For example, improper excavation in vicinity to banks can create an unstable slope condition. Heavy surcharge load on top of bank that overstress the slope will cause shear failure of the subsoils.

2.5 Vegetation

The roots of vegetation covering the surface of slope will form a network under the slope surface which may reinforce soil shear strength. Brush, crab grass, and young and mature tress may perform more roles other than reducing surface water velocity and controlling groundwater activity. The vegetation may minimize soil erosion and also could form a thick insulating layer to reduce deep frost penetration, limiting its adverse effects during and after the long months of a cold Canadian winter. Vegetation stabilization is most effective along relatively small watercourses; however, vegetation may influence channel development or flood drainage in a major river.

2.6 Erosion

Minimizing the impact on the environment and the tableland of a river valley is a challenge typical faced. Soil erosion occurs by the effect of a cyclic freezing-thawing on the properties of soil, high water level fluctuation and flood level. Soil erosion may start as sheet erosion first, followed by gully erosion and mass movement (Linsley et al., 1975). Soil erosion on natural slopes may change by improving the slope cover condition, but the possibility of internal erosion may occur due to hydraulic gradients (groundwater seepage).

Soil erosion due to freezing and thawing may happen in the following ways:

- Thermal cracks may be created during long winter seasons if the shrinking stress of a frozen soil exceeds the maximum tensile strength of the frozen ground.
- Water may easily infiltrate into the cracks directly and form a channel flowing downwards to the toe of the slope along cracks formed during the winter.
- The rapid flowing water may cause substantial internal soil erosion with a steep hydraulic gradient to loose soil material, forming an open cut channel, which makes the erosion area enlarge dramatically.

3. SLOPE STABILITY ANALYSIS AND SETBACK

3.1 Slope Stability Analysis Method

Numerical modeling approaches for slope stability includes finite element method and limit equilibrium modelling etc. The finite element method may be useful for modeling the effect of seepage forces, and can incorporate creep deformation and dynamic analysis and considers soil stress-strain relationships (Jia, 1994).

Limit Equilibrium Methods are currently used in analysis for slope stability and they contain factors of safety to prevent the occurrence of a soil shear failure. The limited equilibrium method included those of Taylor, Bishop, Bishop and Morgenstern, Morgenstern and Spencer, etc (Fang, 1990). The Bishop method of slices is used if a slope consists of several types of material with different values of c and φ and if the pore pressures u in the slope are known or can be estimated. Bishop's Simplified method considers normal interslice force without shear force.

The shearing strength of soils along the arc, based on the effective stress, is determined by:

$$s = c' + \sigma' \tan \varphi' \quad [1]$$

Where
- s is shear strength
- σ' is effective normal stress
- c' is effective cohesion
- φ' is effective angle of internal friction

The factor of safety is given by the ratio:

$$F = s/\tau \quad [2]$$

Where τ is the shearing stress generated by the weight and surface load

3.2 Setback

Setback can provide protection from unexpected catastrophic events and damage or loss due to sudden failure in one weak link of a bank stabilization system, and it allows for maintenance of a natural buffer between the structure and the water body. However, the setback determination is subject to uncertainty factors in future toe recession rates, safety stable slope angles, and adequate bank protection mechanism.

The assessment of erosion setback is normally coupled with field investigation and data analysis. Field work mainly is to define if the bank of the channel/creek is in active erosion, and to survey the distance from the tributary to the toe of the existing slope. This is followed by quantitative computation of competent velocity and channel velocity under 100 years cycle v_{100}. Competent flow velocity v_c is the flow which the bed soil/material in the channel can sustain without erosion or scour, and it can be estimated as:

$$v_c = cR^{\alpha} \quad [3]$$

Where c is a coefficient regarding sediment deposit or erosion start up, and R is the hydraulic radius and can be determined as

$$R = \frac{A}{x} \quad [4]$$

Where A is the computed section area of discharge
χ is the wetting perimeter

and

$$x = b + 2h\sqrt{1+m^2} \quad [5]$$

Here b is the bottom width, h is the height of the bank and m is the inclination of the bank slope of the tributary channel.

Compare the results of computed channel velocity and competent velocity, if

$$v_{100} \geq v_c \quad [6]$$

erosion setback has to be considered. The magnitude of erosion setback is closely related with the existing slope/bank conditions. If the existing bank is in active erosion, the corresponding setback that might be required is relatively larger.

Like normal slope stability analysis/assessment, Factor of Safety (FS) was used in quantitative evaluation for slope stability/potential failure for land development, road construction and subsurface utility installation, which is in the area close to the edge of a long-term safe slope.

A suitable approach provides an economical safe distance to its development. For ravine with watercourse in which flood plain is part of the erosion allowance, the minimum setback will be 15 m in cohesionless soils (silt, sand, etc.); 8 m in cohesive soils (silty clay, etc.), and 5 m in shale bedrock (CVC, 1992).

4. CASE STUDIES

4.1 Multi-Use Development

4.1.1 Project Description

The project site for multi-use development is located southeast of Teston Road and Weston Road, City of Vaughan, Ontario. The ground surface of the site is relatively flat in the south and changes to rolling hill to the north. The Purpleville creek, a tributary of the Humber River, is located in the northwest part of the property. The face of the terraced ravine banks is generally heavily vegetated and evidence of surface slide and revegetation is exhibited. The banks are 10.0 to 16.0± m in height with a slope of 1V:3H at upper banks and 1V:2.5H in lower banks. The steep slope occurs in the areas where toe and surface slide occur.

A storm water management (SWM) pond will be constructed in the northwest sector of the property on the upper section of the bank (El. 238± m) and the lower section of the bank (El. 227± m). It involves a lower facility and upper facility. The projected normal water level of the pond is at El. 231.85 m and El. 224.00 m, respectively, for the sediment forebay at the upper facility and for the lower facility; the bottom of the pond of the upper and lower facilities is at Els. 229.70 m and 223.50 m, respectively. The 100 year flood levels are Els. 233.75 m and 224.75 m, respectively, for the upper and lower facilities. Figure 1 shows simplified stratigraphic cross-section.

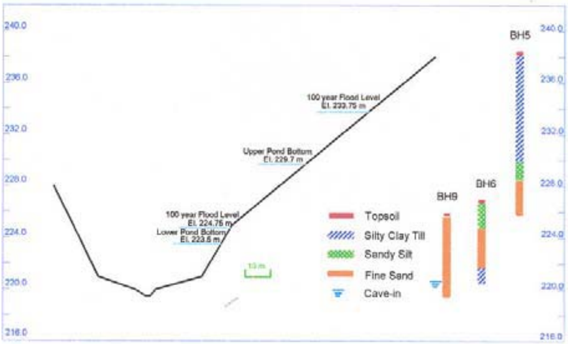

Figure 1. Cross Section and Subsurface Profile

4.1.2 Field Investigation and Subsurface Conditions

The field work was carried out by Soil-Eng Limited. Field work, consisting of advancing 9 boreholes to depths ranging from 6.6 to 12.7 m, was performed on September 29 and 30, 2003. Boreholes 5, 6 and 9 (Borehole Logs shown in Figure 1) will be used in slope analysis.

Subsurface conditions encountered at the project site are summarized in Table 1.

Table 1 – Soil Properties

Soil Type	Property		Elev. (m)**
Silty Clay Till	Water Content W_N (%)	11 to 26	230.0 to 238.5
	Liquid Limit W_P (%)	24& 25	
	Plastic Limit W_L (%)	15	
	Permeability k (m/s)*	1×10^{-7}	
Sandy Silt	Water Content W_N (%)	7 to 20	224.0 to 230.0
	Permeability k (m/s)*	1×10^{-4}	
Fine Sand	Water Content W_N (%)	4 to 17	219.3 to 228.0
	Permeability k (m/s)*	1×10^{-3}	

*Estimated from Grain Size
** Based on Boreholes 5, 6 and 9

- Stratigraphy Structure: the investigation has disclosed that the bank is underlain by a stratum of firm to hard, generally hard silty clay till, overlying strata of dense sandy silt (Els. 228.5 to 230.0 m) and loose to very dense fine sand (El. 219.3 to 225.9 m) beneath sandy silt, in place, overlying the silty clay till deposit. This shows the upper pond will extend into the relatively pervious sandy silt stratum and the lower pond will extend into the pervious fine sand on which the creek meanders.
- Groundwater at the locations where the ponds are proposed is at El.221.0± m which is close to the water level in the creek.

4.1.3 Stability Analysis

A slope stability analysis was carried out at typical cross section A-A at the upper bank and B-B at the lower bank. Section A-A is 10 m high with a slope of 1V:3H, and Section B-B is 4.5 m high with a slope of 1V:2.2H.

The analysis was carried out using the drained parameter shown in Table 2.

Table 2 - Stability Analysis Parameters

Soil Type	Unit Weight* (kN/m^3)	Effective Cohesion* (kPa)	Effective Internal Friction Angle*(°)
Silty Clay Till	21.5	5	33
Sandy Silt	20.0	0	35
Fine Sand	21.0	0	35

* Estimated based on BH data

The water level condition used in the analysis reflected stability of bank in cases: (I) in the natural bank; (II) water raising to 100 year flood levels, and (III) water in pond which has seeped into and saturated the bank mantel. The parameter of soils will need to be changed in these difference cases.

Table 3 – Results of Safety Factor

	(I)	(II)	(III)
Section A-A	1.93	1.93	0.89
Section B-B	2.54	2.23	1.08

The triggering mechanism for movement of the slope appears to be related to the increasing the water level of the pond. According to the Table 3, in the case of natural bank (I) and if the water level in the SWM pond rises to 100 year flood levels (II), the safety factors are larger than 1.5, indicating the slope is geotechnical stable; however, if the water in the SWM pond saturates the mantel of the bank (III), the safety factor of the slope is reduced to 0.9 and 1.1 in the upper and lower ponds, respectively, indicating the banks of the upper facility and lower facility is in an unstable condition.

In order to prevent the occurrence of localized surface slides and to enhance the stability of the bank, the following geotechnical constraints should be stipulated:

- The prevailing vegetative cover must be maintained, since its removal would deprive the bank of the rooting system that reinforces against soil erosion by weathering.
- Measures must be taken to prevent retention of stormwater from saturating the bank mantel, such as,

lining the pond with geosynthetic clay layers and the installation of subsoils.

- The leafy topsoil cover on the bank face should not be disturbed, since this provides insulation and screens against frost wedging and rainwash erosion.

4.2 Condominium Development

4.2.1 Site Description

The site is located at 1695 The Collegeway, City of Mississauga. It consists of a weed and grass covered open field with some scattered immature trees. Two buildings are located to the west of the investigation area. The proposed development will consist of a 22-storey condominium building with 3 levels of underground parking and two 3- to 4- storey stacked skylight apartment buildings. The Sawmill Creek, a tributary of Credit River, crosses the east boundary of the site.

The overall natural bank ranges in height from 10 to 12 m and has a slope of 20° to 30° (1V:1.7H to 2.7H). In places, it slopes at 45° (1V:1H) at the top section, at 28° (1V:1.9H) at the middle section, and 15° (1V:3.8H) at the lower section. The creek bank has a flood plain, 10 to 28 m wide, from the toe of the defined bottom of the bank to the creek. The face of the bank slope is generally densely wooded and weed-covered. Visual inspection indicated that minimal creeping occurs at the top section of the slope. The middle and bottom sections of the slope were free of sloughing and generally in a stable condition. The inspection also revealed no sign of seepage.

4.2.2 Field Investigation

The field work consists of 5 BoreHoles (BH), in which, BH 5, to a depth of 15.4 m was used to analyze slope stability. The investigation has disclosed that beneath a veneer of topsoil and a layer of sandy silt fill (1.8± m in thickness), the existing bank is generally underlain by strata of very stiff to hard, generally hard silty clay till, with very dense sandy silt and silty fine to medium sand in the lower zone of the soil stratigraphy.

The groundwater was detected in the stratum of sand silt at a depth of 12.3 m (El. 110.7 m) during the investigation, and the groundwater level is lower than the toe of the bank.

4.2.3 Stability Analysis

The overall long-term stability of the natural bank is primarily governed by the effective internal friction angle of the revealed bank stratigraphy. Its subsurface condition, as disclosed by BH 5, was analyzed using Slope W Version 4 Software developed by Geo Slope International Ltd. The parameters used for the analysis are presented in Table 4.

Table 4 – Stability Analysis Parameters

Soil Type	Unit Weight* (kN/m^3)	Effective Cohesion* (kPa)	Effective Internal Friction Angle*(°)
Sandy Silt Fill	21.0	0	28
Silty Clay Till	21.5	5	32
Sandy Silt	21.0	0	35
Silty Fine Sand	21.0	0	35

* Estimated based on BH data

The overall long-term stability of the bank was analyzed using Limit Equilibrium Criteria using the Bishop method. Cross Section A-A is shown on Figure 2.

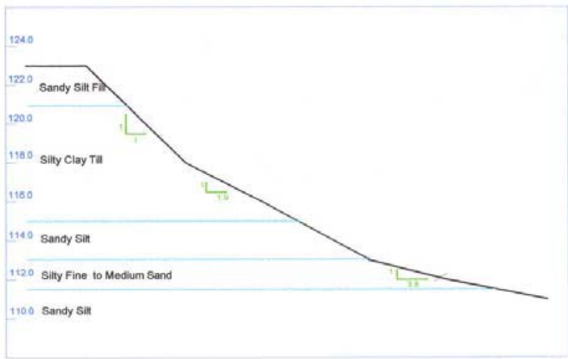

Figure 2. Cross-Section A-A

The stability in three gradient slopes (36°, 25° and 22°) have been analyzed with the results shown in Figure 3.

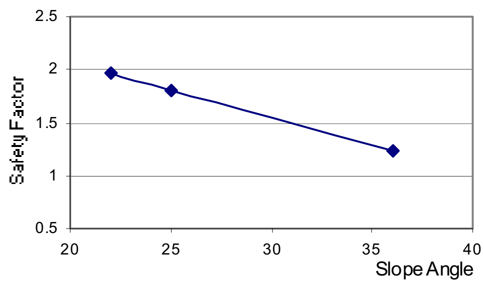

Figure 3. Safety Factor vs. Slope Angle

- Figure 3 illustrates the slope inclination impact on the safety factors. Critical slope angle with safety factor of 1.5 is 31.5°.
- The factor of safety against relatively shallow sliding type failure at the top section of a natural slope is 1.085. This indicates that the slope is only marginally stable with respect to relative shallow type failure and creeping will likely occur for the slope steeper than 1V:2H.

- The long term stable slope lines based on the Credit Valley Conservation Authority (CVCA) approach are at 1V:2.5H. However, based on the site condition and stability analysis, a factor of safety of 1.5 is achieved for slope of 1V:2.1H, which meets the guideline from the Ontario Ministry of Natural Resources (OMNR).
- An erosion allowance of 8.0 m, to provide an adequate buffer against possible abuse, should also be incorporated in areas where the creek meanders at a distance of less than 15 m from the toe of the bank.
- The proposed building will contain 3 levels of underground parking and the lowest level will be at El. 111.90 to 113.35 m. This will have a positive impact on the existing slope stability. With the use of a properly designed and constructed shoring structure for the underground parking construction, the proposed building construction will not impose adverse impacts on buffer areas.

5. DISCUSSION

The following presents a summary of the critical facets associated with the slope analysis of banks in the vicinity of rivers.

- Field investigation, site inspection and measurements of the slope provides useful information on soil composition, the shape, and magnitude of slope movement or erosion. The composition and inclination of slope, soil structure and groundwater govern the stability of the slope.

- Stable slope line can be determined based on the results of slope stability analysis, and it incorporates the policies of the govering conservation authority; the stable slope line recommended by the geotechnical engineer may vary from experience accumulated by the local environmental agency which takes into account the yearly changes in weather conditions, groundwater fluctuation and human activity.

- The setback limitation related to the physical characters of the bank of valley. The setback is considered as a safe distance based on the available information and guideline of local land use. However, setback limits can be reduced if a geotechnical engineer submits new information confirming the stability of the bank.

- Stability of the slope requires preventing erosion and scour; a stormwater management pond requires lining to prevent runoff erosion. A geosynthetic clay layer is normally used to improve the performance of pond.

- Bioengineering reinforces the soil slope and preserves beneficial environmental conditions.

- The bank in the vicinity of a river quite often has poor soil conditions, such as organic deposits, flood plains and soft clay or debris fill. The *Geopier* (Fox, 2001) soil reinforcement is highly effective as a means of stabilizing a failing slope, and providing global stabilization within weak foundation soils. Reinforced *Geopier*–soil zones increases the safety factors against slope instability.

- The stability of a slope may be reinforced by various system, i.e., Armour Stone, geogrid, gabion, soil nail, shoring structures and retaining walls etc. They have been applied in engineering practice to strengthen the stability of slope near creeks and rivers.

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