GEOTECHNICAL ASPECTS OF STABILIZATION OF HIGH, STEEP, ACTIVELY-ERODING SHORELINE CLIFFS - THE SCARBOROUGH BLUFFS, LAKE ONTARIO

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ABSTRACT
The Scarborough Bluffs (high, steep cliffs) comprise approximately 15 km of the Lake Ontario shoreline, in the easterly part of the amalgamated City of Toronto. The Bluffs are composed of Pleistocene deposits and tower in places over 90 m above lake level. The Bluffs have been actively eroding and retreating for centuries. Erosion has been both by wave action on the lake side and major gulley formation from the land side. In the course of the growth of Metropolitan Toronto, the tableland adjacent to the crest of the Bluffs has had intensive building activity. Because of this, and the continual erosional processes, stabilization of the Bluffs had special significance in terms of minimizing long-term erosion losses.

In 1979, the Toronto and Region Conservation Authority (TRCA) initiated studies with the objective of producing a Master Plan for stabilization of the Bluffs, the development of which clearly required concurrent thought of a wide variety of items such as environmental considerations; property costs; construction materials; scheduling; shoreline erosion processes; geotechnical matters; and the like. The overall studies included a comprehensive geotechnical engineering program, which is the main topic of this paper. In a geotechnical sense, the project was unusual in a number of important respects.

The paper describes the geotechnical studies performed; provide details of representative remedial works carried out; and comment on monitoring and performance of the Bluffs in the 20 year interval since the remedial work began.

RÉSUMÉ
Les falaises abruptes des Scarborough Bluffs couvrent environ 15 kilomètres de la côte du lac Ontario, et sont situées à l'est de la ville amalgamée de Toronto. Les Bluffs sont composés de dépots pléistocènes, et à quelques endroits mesurent plus de 90 m au-dessus du niveau du lac. Pendant des siècles l' érosion a entrainé l'effondrement des falaises. Au bas des falaises elle fût causée par les vagues du lac Ontario tandis que son sommet subisait les effets de la formation de ravins. A cause de la croissance du Toronto métropolitain les Bluffs ont connu une activité intensive au niveau du dévelopement residential et commercial. Pour cette raison et afin de limiter les pertes causées également par les effets du processus continuel de l'érosion, la stabilisation des Bluffs devient très importante.

En 1979, l'autorité de conservation de Toronto et de la region décide de lancer une étude avec comme objectif la production d'un programme-cadre visant à la stabilisation des Bluffs. Le développement de ce programme se doit d'inclure une grande variété de considerations environnementales tel: le coût des propriétés, les matériaux de construction, l'établissement du programme, le procédé d'érosion du rivage, les sujets géotechniques et autres. Les études de combinaison doivent également inclure un programme complet de technologie qui est la matière première de cet article. Dans un sens géotechnique, ce projet est peu commun à cause d'un grand nombre d'égards importants.

Cet article décrit les études géotechniques réalisées, et fournit les details de travaux réparateurs representatifs menés à bien. Il décrit les commentaires sur la surveillance et l' exécution de ces travaux depuis qu'ils ont commencés il y a 20 ans.

1. BACKGROUND

The Scarborough Bluffs (Bluffs) extend approximately 15 km along the north shore of the Lake Ontario shoreline, in the easterly part of the amalgamated City of Toronto. The Bluffs are composed of an extensive thickness of generally flat lying Pleistocene deposits, which range from Illinoian to Late Wiscosinan in age. The height of the slopes along the Bluffs varies from about 50 metres (m) to greater than 90 m above the present day level of Lake Ontario, approximately Elevation 75 m. A photograph of the Bluffs near Livingston Road is given in Figure 1 to illustrate their general appearance.

Figure 1. Example of Gully Development (Geocon, 1980)

The Bluffs have been actively eroding and retreating for centuries. Erosion has been the result of both wave action on the lakeside and major gulley formation from the land side. The pattern of erosion has been influenced to varying degrees by such factors as wave action, soil conditions, groundwater, lake levels, construction activities, and the like.

In the course of the growth of Metropolitan Toronto, the tableland adjacent to the crest of the Bluffs has had intensive building activity and has become increasingly important from both social and economic standpoints. Because of this, and the continual erosional processes, stabilization of the Bluffs had special significance in terms of minimizing long-term erosion losses and resultant adverse economic impacts, etc.

Over the years, many types of remedial works have been applied in local areas along the Bluffs, by a variety of different individuals and agencies. However, these had very limited success largely because of the fragmented approach taken. In addition, the application of an improvement would in many cases adversely influence properties down drift of these improvements.

TRCA, which has jurisdiction over the Bluffs, recognized that the only effective way of stabilizing the Bluffs was to do so systematically in accordance with an overall Master Plan. Their ultimate goal was to undertake a comprehensive program of shoreline management designed to prevent, eliminate, or reduce the risk of hazard to life and property, while cognizant of the natural attributes of the lakefront setting.

In 1979, TRCA initiated studies with the objective of producing the requisite Master Plan, the development of which clearly required concurrent thought of a wide variety of items such as environmental considerations; property costs; construction materials; scheduling; shoreline erosion processes; geotechnical matters; and the like.

Experience with the assessment and stabilization of slope retrogression along shorelines had typically been addressed previously by coastal engineers and not from a geotechnical perspective. As such, precedent for such a geotechnical study was not readily available causing the study team to draw from indirectly related precedent such as the performance of steep cuts associated with strip mining, stability of fills built by top dumping, and the like.

TRCA decided on a staged approach to stabilization of the Bluffs, as discussed below, and an overall strategy which included four main components namely field studies, arresting toe erosion, utilizing self-stabilization to the extent practical and maintaining effective drainage.

As an undertaking in slope stabilization works, this project is unusual in a number of important respects from a geotechnical standpoint. These include the overall size of the Bluffs, the constant retreat due to toe erosion, the significant influence of self-stabilization, and the need for remedial measures to encompass a number of adjacent slopes in order to be effective.

The findings of the geotechnical studies are the main topic of this paper.

2. APPROACH TO STUDIES

The studies were carried out in two main phases as discussed below.

2.1 Phase 1

Due to the large aereal extent of the Bluffs, the initial approach was to establish a general picture of the soil conditions along the length of the Bluffs and then subdivide the shoreline into a series of sectors with inherently different stabilization solutions. This approach was in contrast to most slope stability studies where individual areas are generally assessed and specific measures are then put forward. As discussed above, in the case of the Bluffs, various remedial measures had already been implemented with varying degrees of success. More importantly though, the implementation of these measures had been piece-meal and one positive action had a tendency to result in increased erosion elsewhere. Consequently, it was elected to assess the entire length of the Bluffs in order to better understand their behaviour overall, from an erosion standpoint.

The primary purpose of this phase was to provide a preliminary appraisal of geotechnical conditions and develop preliminary design parameters. To accomplish this, Phase 1 was divided into a series of tasks, as follows:

The first task included an assembly and review of pertinent background data including geological reports, topographic drawings, air photos, oblique air photos, location of services, past engineering reports and the like. To better keep track of these data, it was catalogued and wherever possible transferred graphically to drawings. Map sizes were quickly standardized in the study so that data from one task could be easily compared and/or overlain with data from another task. These maps proved invaluable throughout the studies.

A site reconnaissance was then conducted along the length of the Bluffs in order to develop an inventory of their physical condition. This was accomplished by scaling the Bluffs at a number of locations noting geological contacts, areas of seepage, location of past fills and remedial measures. The surficial mapping was aided by previous mapping conducted by Dr. Paul Karrow (1967) and the use of oblique air photos to extrapolate contacts. Unlike many geotechnical evaluations, the majority of the contacts were visible along the length of the study area. Data from the mapping program was transferred to a series of oblique geological sections.

A generalized stratigraphy along the length of the Bluffs as produced by Sado and Powell (1984) is shown on Figure 2 along with a schematic cross-section excerpted from Karrow and Morgan (1975).

A detailed subsurface exploration program was also conducted at a number of existing talus slopes, with a characteristic "rooster tail" shape, which had formed at the base of the Bluffs where toe protection against erosion had been previously placed. The objective of this program was to assess the internal structure and drainage of the talus slopes, which evolved after bluff toe protection. The results of this task would later be used to make initial predictions of the slope configurations which would be expected to develop in the long term, behind such toe protection. Drilling of these sites was accomplished with a motorized tripod rig and standard sampling equipment.

The data obtained suggested that the talus slopes were to an extent, underdrained as indicated by downward flow and a low phreatic surface when the total precipitation was minimal. However, the stratified nature of some of the talus also suggested they may give rise to significant piezometric pressures. Some of the talus material, although being slumped, was reasonably intact and not in a remoulded condition. For stability analysis of the talus slopes, the interlump strength was believed to be the more critical for the undrained behaviour of the talus, not the general firm to stiff strength.

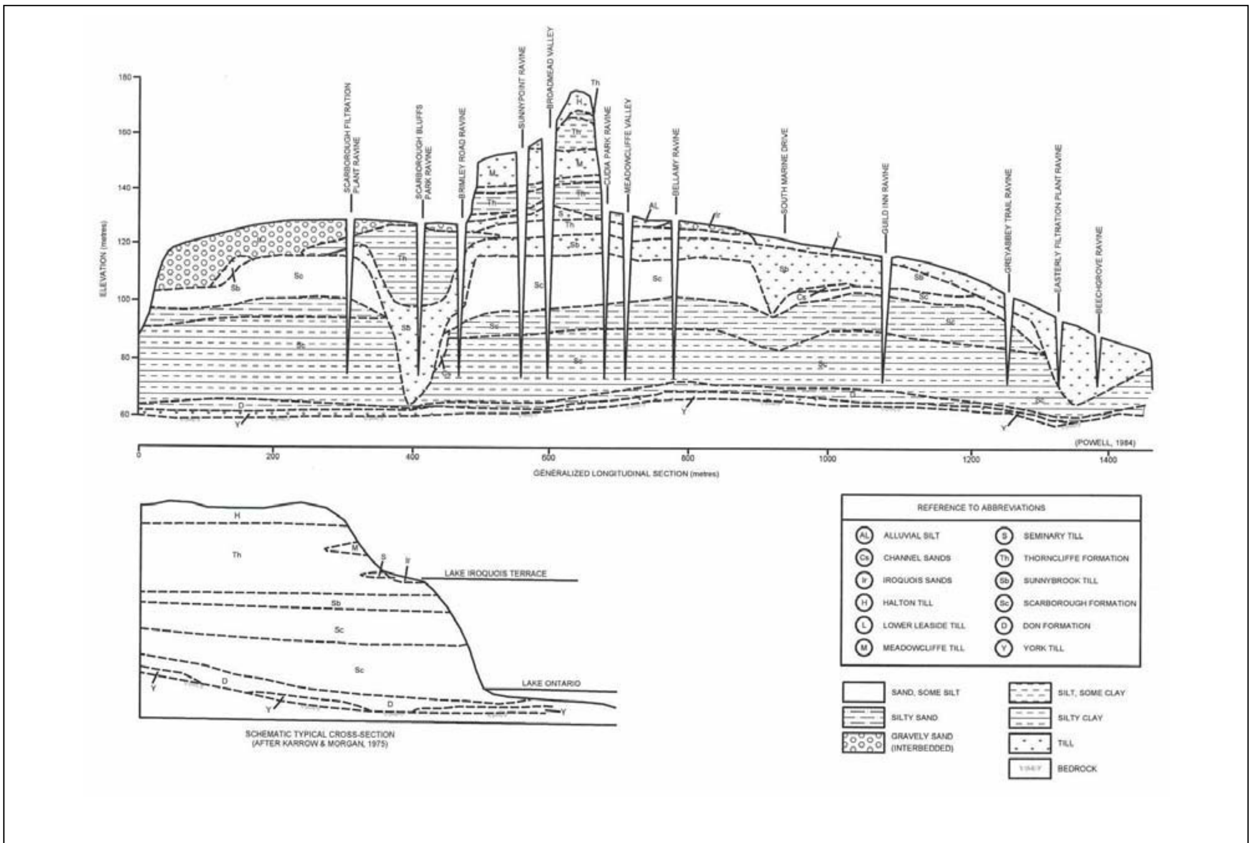

Figure 2. Generalized Stratigraphy (Sado & Powell, 1984)

The development of talus was found to be seasonal, in that during the spring and summer months groundwater movement would result in the undercutting and down slope movement of sands and intact chunks of till. However, during late fall and winter months, as a result of freeze-thaw cycles, the majority of material build up was in the form of small lumps of till. Surface water movement down the slope would later remould the latter material.

As previously discussed, private, commercial and governmental agencies had introduced many forms of local remedial works along the Bluffs, with varying degrees of success. As part of Phase 1, a review of their performance was undertaken to better understand the effectiveness of filling over the crest of the Bluffs, protecting the toe, and alterations to seepage exiting the face of the Bluffs. This work was done concurrently with an assessment of the rates of slope retrogression and details of failures along the Bluffs. Much of this work was done by reviewing historic aerial photographs at the University of Toronto Library together with a site reconnaissance.

Average rates of erosion (slope retreat) were determined from the literature to be in the range of 0.31 m/yr (Bird & Armstrong, 1970) to 0.49 m/yr (Coleman, 1933). However, reported rates varied from as high as 2.04 m/yr to as low as 0 m/yr (Environment Canada, 1975). A preliminary attempt was made in Phase 1 to update the rates of retreat. However, it was discovered that a primary source of reference was a sketch rather than a scaled drawing and as such it was not felt during Phase 1 that recession rates should be used as a major criterion in preliminary sectorizing of the Bluffs for remedial stabilization purposes. However, it was concluded that this area required additional study due to its important influence on establishing priorities and details for the stabilization of the Bluffs.

It should however be noted that aerial photographs did indicate areas where the most active slope instability was occurring. In this regard, it was also found that the slope movement was cyclic. That is, after an approximate 3 1/2 year delay from a period of high lake levels a dramatic increase in surficial landslide activity took place along the length of the Bluffs. This time delay was thought to be the result of the undercutting of the slope and subsequent softening of the clayey soils resulting in failure of the slope. Where the highest activity was taking place, South Marine Drive, the offset (time delay) was uncharacteristic and only about one half of a year.

Upon completion of the Phase 1 tasks, an initial sectorization of the Bluffs was conducted based on soil conditions, groundwater, geological conditions, historical events, land use at the crest, and anticipated types of remedial measures.

It was concluded that the concept of constructing primary shoreline protection together with some secondary remedial measures, for the purpose of stabilizing the Bluffs as a whole, was feasible from the standpoint of the geotechnical factors involved. This was an important finding.

2.2 Phase 2

The principal objective of Phase 2 was to provide the geotechnical information required for development of the Master Plan in principle. However, in view of the complexity of the Bluffs, it was evident that the formal Master Plan would have to be developed later with concurrent consideration of a variety of factors in addition to items of geotechnical importance.

This Phase focussed on five main areas, including:

1. An extensive study related to the rates of retreat of the crest and toe of the Bluffs.
2. A limited field exploration program to permit an initial appraisal of soil and groundwater conditions within various sectors along the Bluffs.
3. Initial stability assessment of various slope profiles along the Bluffs to better assess short and long term stability and estimate the long term slope profile developed by self-stabilization.
4. Development of different schemes to stabilize the Bluffs based on both surface and subsurface conditions.
5. Development of a Master Plan outline based on geotechnical considerations alone.

The following sections present a summary of the findings of each of the above areas.

2.2.1 Rates of Retreat

To better evaluate the rates of retreat along the Bluffs, historic mapping and aerial photography were again compiled and various crest positions were triangulated to common features and then compared to one another. Based on this analysis for a 68-year time frame (1922 to 1980), an average annual rate of retreat was determined to be 0.38 m/year (Geocon, 1982). However, at any one place the annual rates tended to be misleading in the sense that some tableland may be lost instantaneously (such as in the case of a block failure), whereas other areas erode progressively with time. To better assess the way in which the Bluffs tended to retrogress, a series of cross-sections were developed and compared using topographic mapping from 1972 and 1980. This work not only assisted in evaluating the way in which the slopes retreated but also how the slopes tended to self-stabilize when the toe protection was provided. Figure 3 illustrates one of the profiles developed from this work.

There were essentially four major modes of failure, which took place along the Bluffs. These included;

a) Block failures, tended to occur in the hard cohesive soil units, where well-developed joint sets were present. The extent of this form of failure was dependent on lake levels and subsequent amount of undercutting at the toe, build up of pore water pressures in the joint sets, softening due to saturation and/or a combination of these effects.

b) Internal erosion and undercutting of the slope, at points of groundwater discharge was the most prominent cause of erosion along the Bluffs. As discussed in more detail later, and illustrated in Figure 2, the Bluffs are comprised of a number of horizontal interbedded sands and till/clay units. As such there are a number of perched water conditions due to permeability contrasts between the various units. The most notable example of this is at the contact between the Scarborough Sand and Scarborough Clay Units. (See also Table 1).

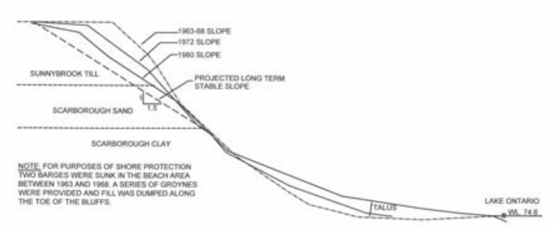

Figure 3. Example of Rates of Retreat Profile (Geocon, 1982)

It was noted that when the groundwater seeps at a high hydraulic gradient towards the slope face it tends to form a "pipe" which with time expands due the increased water flow and internal erosion of the sandy soil. As the pipe increases in size the overlying soil is progressively undercut and fails in a circular arc manner. This manner of failure is the most common in the development of large running gullies along the Bluffs. The development of these gullies is often very rapid and therefore requires immediate remedial action to be taken.

The rate of crest retreat as measured in later studies could be in the order of 3 m to exceptionally in excess of 21 m/year depending on location (Geocon, 1983; Gartner Lee, 1986)

c) Slumping along South Marine Drive, an approximate 0.3 km sector of the Bluffs, resulted in the rate of crest retreat on the order of 1.1 to 1.4 m/year. In this area the upper slope retrogressed by successive slides. The slide debris moved progressively down to the toe of the slope where it was later eroded by wave action. Parker et al 1986, described how the presence of this debris at the toe of the slope worsened stability by blocking the natural drainage of the slope, which subsequently resulted in a larger landslide.

d) Mud flows tend to take place in the gullies and within the talus piles along the Bluffs. They are the result of the saturation of previously failed loose material. These mud flows cause an on going maintenance problem along areas where only toe protection works have been constructed.

It should be noted that no evidence of deep-seated failures of the Bluffs were identified during the course of the subject studies.

2.2.2 Subsurface Conditions

A total of 24 boreholes were advanced from both the crest and toe of the Bluffs in Phase 2. The boreholes, which were advanced to a maximum depth of 69.49 m, were used to obtain undisturbed and disturbed samples and facilitate installation of piezometers. Table 1 provides a brief description and selected engineering properties for design, for the major stratigraphic units from youngest to oldest, based on the exploration program and later laboratory testing. The Quaternary Formation names used are after Karrow, 1967, and Karrow and Morgan, 1975. Figure 2 provides a typical cross section and longitudinal section for the Bluffs.

The consistency of the cohesive strata ranged from very stiff to hard. The relative densities of the cohesionless formations varied between compact to very dense. The unit weights of the natural strata were taken at 19.65 kN/m^3 (125 pounds per cubic foot).

Table 1. Geotechnical Properties.

Unit	ϕ' (degrees)	c' (kPa)	Su (kPa)
Lake Iroquois Sands	35	0	n/a
Halton Till	n/a	n/a	n/a
Lower Leaside Till	30	19	n/a
Thorncliffe Clay	30	38	200
Thorncliffe Sand	38	0	
Meadowcliffe Till	30	57	
Seminary Till	n/a	n/a	n/a
Sunnybrook Till	30	19	
@ Bluffer's Park	40	72	500
Scarborough Sand	38	0	
Scarborough Clay	30	57	
Below El. 77 – 75 m	20	10	
Don Sand/York Till, Shale Bedrock	**		

n/a: Not applicable to stability analyses undertaken
** Taken as hard base for stability analyses

2.2.3 Groundwater

As noted above, the general soil conditions in the Scarborough Bluffs consist of an alternating series of flat-lying permeable and low permeability strata. The main permeable strata are the Don Sand overlying bedrock, and the Scarborough Sand. The primary low permeability strata are the Scarborough Clay and the Sunnybrook Till.

Groundwater in these strata enters by surface infiltration from the tableland and slowly seeps downward within both the permeable and low permeable units. In the higher permeable units, water has two possible routes, laterally towards the Bluffs and associated gullies and/or into the underlying lower permeability units. Due to the excellent lateral drainage characteristics of the Bluffs, the pressure heads within the various soil units were found to be small.

As illustrated on Figures 1 and 2 a prominent feature is the intersection of gullies along the central portion of the Bluffs. The presence of these gullies is directly related to the position of the abandoned Lake Iroquois shoreline and/or areas where there is channelled surface or groundwater movement. The significance of their presence, in regard to slope stability, is two-fold. Firstly, they provide an outlet for groundwater movement, thus draining the adjoining tableland and, secondly, where the gullies are closely-spaced' they provide for a higher reserve of stability on account of their three dimensional effect.

2.2.4 Stability Analyses

Based on the results of the field and laboratory programs representative sections were chosen at six locations along the Bluffs to assess their existing stability and projected long-term performance.

Analyses indicated the Bluffs had computed Factors of Safety generally in excess of 1.5 in the case of deep-seated type failures. However, shallower slip surfaces were close to unity indicating marginal factors of safety. The results were consistent with the observed field conditions and the main cause of shallow instability, namely the effects of toe erosion by wave action.

An important question remained unanswered by the above results, namely what would happen if the toe erosion was halted? Would a deep-seated failure then develop? It was realized that if toe erosion was stopped, the dense soils near the face of the Bluffs would become weaker due to expansion and absorption of water. It was also clear that shallow failures would continue to occur and talus would tend to accumulate at the foot of the Bluffs, reducing the average slope inclination. It was anticipated that the net effect would however result in an increase in the stability of the Bluffs. It was recognized, however, that if blockage of drainage was allowed to occur, a significant adverse influence on stability could result.

2.2.5 Stabilization Measures

The observations of performance of the Bluffs were invaluable to the Phase 2 study. In this context, three locations were identified along the Bluffs where toe protection had been introduced previously by others and no other remedial measures performed. As such the process of sloughing and accumulation of talus material at the foot of the Bluffs left the slope to self-stabilize. Comparison of the resulting slope profiles indicated considerable similarity even though the soil stratigraphy of the Bluffs differed in detail from site to site. The inclination of the self-stabilized slopes was initially about 1.2H:1V in its steepest part. Accounting for further flattening, it was concluded the long term slope inclination would be approximately 1.5H:1V, which was consistent with the analytical predication, based on fully softened soil (c'=0, $\phi'=30^{o}$) and downward drainage. This process was also consistent with indirectly related precedent at other project sites.

The concern which remained however was whether or not deep-seated failures were likely to occur. On the basis of preliminary stability calculations made using allowances for possible decreases in strength of the Scarborough Clay, a number of sections incorporating a stabilizing mass at the toe, were developed which confirmed that the Bluffs could be stabilized provided the slopes remained drained internally and an appropriate stabilizing buttress was provided along the toe.

The one section of the Bluffs where self-stabilization was not considered applicable was at South Marine Drive where the observed slides were generally deeper than the surficial slides which were prevalent elsewhere. Erosion trends in both the short and long terms had been substantially above the norm for the Bluffs elsewhere. To put this in perspective, the average crest retreat for the Bluffs was 0.38 metres per year, whereas the average crest retreat along the South Marine Drive sector was 1.3 metres per year. Based on these figures, over 30 homes as well as the roadways and services were considered to be endangered in the South Marine Drive area.

At this location extensive buttressing of the slope and incorporation of drainage measure were carried out. See Figure 4. Parker et al 1986 present a detailed description of this work.

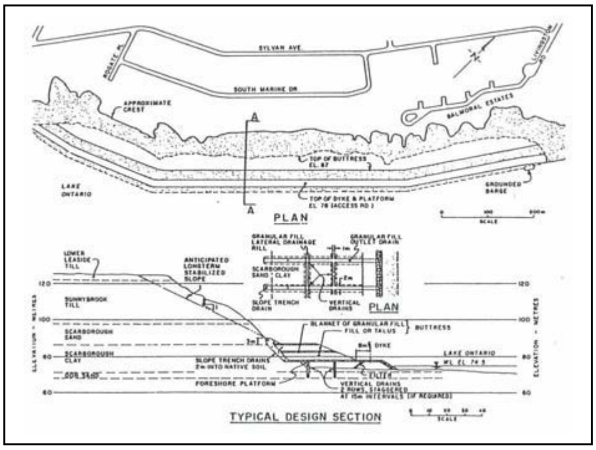

Figure 4. Stabilization Measures at South Marine Drive (Parker et al 1986)

3. MASTER PLAN

The results of Phases 1 and 2, were incorporated by TRCA into a general plan for stabilizing the Bluffs. The concepts included the following items of primarily geotechnical relevance:

1. Stabilizing the Bluffs did not necessarily require maintaining the crest position.
2. Construction work could extend over a long period (decades) allowing specific areas to be treated on a priority basis.
3. Basic to any stabilization scheme was protecting the toe against erosion by suitable means.
4. Considerable amounts of fill would be required. Consideration could be given to using select materials from construction sites in the Toronto area.
5. Over most of the Bluffs, self-stabilization appeared feasible as the main remedial measure.
6. Self-stabilization would however require a commitment to do maintenance.
7. Maintaining drainage was critical.
8. Major gullies would also have to be stabilized.
9. A few areas such as South Marine Drive would require special consideration.
10. The foreshore platform (as in Figure 4) could be wider than necessary purely for erosion protection if excess materials were available.

4. REMEDIAL MEASURES

Since completion of Phase 2, the TRCA has carried out numerous remedial works along the Scarborough Bluffs basically in accordance with the Master Plan. Remedial measures used to date have included construction of toe revetments, groins, horizontal drains and placement of fill over the edge of the slope. The construction of these works has not only provided a form of mitigation but has produced a recreational corridor along portions of the waterfront as well as increasing the economic value of the tableland.

From a recent site reconnaissance of the works completed to date, the process of self-stabilization has been successful. This is illustrated by Figures 5 and 6 which illustrate views of one sector of the Bluffs taken about 20 years apart.

5. ACKNOWLEDGEMENTS

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Figure 5. Looking west along Sylvan Avenue area prior to stabilization works. (Geocon, 1982)

Figure 6. Looking west along Sylvan Avenue area in 2004 showing stabilization works