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NWRI Contribution No. 90-37

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MANAGEMENT PERSPECTIVE

Highly-erodible steep bluffs along the shores of the lower Great Lakes consist predominantly of glacial and glaciolacustrine sediments with different permeabilities. Seepage erosion in these bluffs is widespread and continues even after wave erosion at the toe of the bluffs is discontinued either due to the presence of natural beaches or due to man-made remedial works. Consideration of overall, long-term slope stability of protected bluffs has to be therefore addressed in erosion control projects.

The present paper adresses both the analysis of complex seepage flow in layered bluff slopes and the control of seepage by various de-watering methods. It is shown that the finite element seepage analysis, when combined with field and laboratory geotechnical data, is a suitable and versatile tool to determine the factors of safety at seepage-face locations and to evaluate the design of remedial de-watering measures. The general methodology has been applied to two sites where seepage erosion represents the important mode of bluff retreat. A very good agreement between numerical modelling and field measurements indicates that this approach is physically correct and can be applied to other sites with seepage-erosion problems.

PERSPECTIVES DE LA DIRECTION

Les falaises abruptes très érodables en bordure des rives des Grands Lacs d'aval sont constituées de sédiments essentiellement glaciaires et glaciolacustres à perméabilité variable. L'érosion par infiltration, largement répandue dans ces falaises, se poursuit même lorsque cesse l'action des vagues sur la base (présence de plages naturelles ou ouvrages de protection). Tout projet de lutte contre l'érosion doit donc tenir compte de la stabilité globale et à long terme des versants des falaises protégées.

Le présent article traite : 1) de l'analyse des écoulements par infiltration complexes qui s'observent dans les versants de falaises à couches multiples et 2) du contrôle de l'infiltration au moyen de diverses méthodes d'assèchement. On démontre que l'analyse de l'infiltration à éléments finis, combinée à des données géotechniques de terrain et de laboratoire, est un outil adéquat et polyvalent qui permet de déterminer les facteurs de sécurité à des sites précis d'infiltration sur le front de falaise et d'évaluer les mesures d'assèchement. Les méthodes générales ont été appliquées à deux sites où l'érosion par infiltration représente le mode le plus important de recul. La modélisation numérique et les mesures réalisées sur le terrain concordent très bien; l'approche est donc correcte sur le plan physique et peut être appliquée à d'autres sites présentant des problèmes d'érosion par infiltration.

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ABSTRACT

The toe stabilization of high bluffs against wave erosion, when successful, creates marginally stable natural slopes that most likely require artificial drainage systems in order to maintain long-term stability. In many cases, seepage erosion, occurring at the interface between granular and cohesive strata, is responsible for continuous erosion of the bluff face. The finite element seepage analysis is recommended for heterogeneous slopes to determine the factor of safety against seepage erosion and to assess the efficiency of a proposed drainage system. Two examples of the site-specific application of the method are presented.

RESUME

La stabilization efficace du pied des hautes falaises, qui le protège contre l'érosion par les vagues, entraîne la création de pentes naturelles peu stables dont la stabilité à long terme exige très probablement l'installation d'un réseau de drainage artificiel. L'érosion par infiltration, qui se produit à la surface de contact des couches granuleuses et des couches cohérentes, est souvent responsable de l'érosion continue de la paroi de la falaise. On recommande d'utiliser, dans les pentes hétérogènes, l'analyse de l'infiltration par éléments finis pour déterminer le coefficient de sécurité contre l'érosion par infiltration et pour évaluer l'efficacité de tout réseau de drainage proposé. On donne deux exemples de l'application de la méthode à des lieux particuliers.

INTRODUCTION

High bluffs undergoing active toe erosion by waves are characteristic for much of the shoreline of the lower Great Lakes. The bluffs may consist of one or more layers of glacial and glaciolacustrine sediments of contrasting permeability. The protection of a high bluff slope against wave attack produces a marginally stable slope that may undergo significant morphological changes over a period of several decades (Welch, 1972). For this reason, it is imperative to determine the long-term stability of the bluff slope. Stabilization of bluffs by drainage and other measures, e.g., adding

weight at the toe of the bluffs, slope flattening or installation of retaining walls should be viewed as an important component of shore protection measures. Where shore bluffs consist of a single stratigraphic unit and the material and geometric information is known, it is possible to assess the state of stability of the bluff slope by means of slope stability charts (Vallejo and Edil, 1979). Multi-layered slopes, with complex patterns of groundwater flow, require more complicated computations using existing limit equilibrium methods. Efficient software packages for microcomputers are by now available, which permit to perform comprehensive slope stability analyses for most of the commonly used methods of slices.

In this paper, attention is drawn to erosion problems caused by seepage at the interface between layers of different permeability. The bluff instability is caused by groundwater seepage rather than by rotational sliding. As stability calculations based on limit equilibrium methods assume a different failure mechanism, their application may lead to completely misleading results. Seepage erosion is of regional importance on the east shore of Lake Huron, on the central north shore of Lake Erie and on the north shore of Lake Ontario. Hutchinson (1982) gives an account of widespread seepage erosion in coastal cliffs in England.

FINITE ELEMENT SEEPAGE ANALYSIS

The finite element method appears to be well suited for the analysis of seepage erosion in shore bluffs, as it can easily take into account soil anisotropy and heterogeneity. The finite element program PC-SEEP (Geo-slope Programming Ltd., 1987) can handle complex two-dimensional transient saturated-unsaturated flow through heterogeneous and anisotropic materials. In this paper, only steady-state analyses are discussed, which are of sufficient accuracy in view of the position and documented fluctuation of the phreatic surface at the two sites investigated. Transient analyses would be likely required for cases where the fluctuation of the phreatic surface is rapid or where seepage erosion occurs in the proximity of the bluff crest.

FACTOR OF SAFETY AGAINST SEEPAGE EROSION

As a result of the analysis, the position of the phreatic surface and the distribution of pressure heads throughout the bluff slope are obtained. For the approach adopted here, it is important that hydraulic gradient vectors, determined by their magnitude and orientation, are also obtained. Following the work by Kovacs (1981) and Iverson and Major (1986), it is posssible to derive equations for the critical hydraulic gradients at seepage-face locations (Zeman, 1989). Local factors of safety are then computed as ratios of the critical hydraulic gradient and the hydraulic gradient obtained for the same vector orientation. In general, the analysis can be performed for both cohesionless and cohesive soils. The stability against seepage erosion depends on slope geometry, magnitude and orientation of the hydraulic

gradient vector (Fig. 1) and soil geotechnical properties. The most adverse direction for seepage is obtained for the direction

$$\alpha_{cr} = \phi' - \beta \qquad (1)$$

where α is the angle of the hydraulic gradient vector with the horizontal, ϕ' is the effective friction angle and β is the slope angle (Fig. 1).

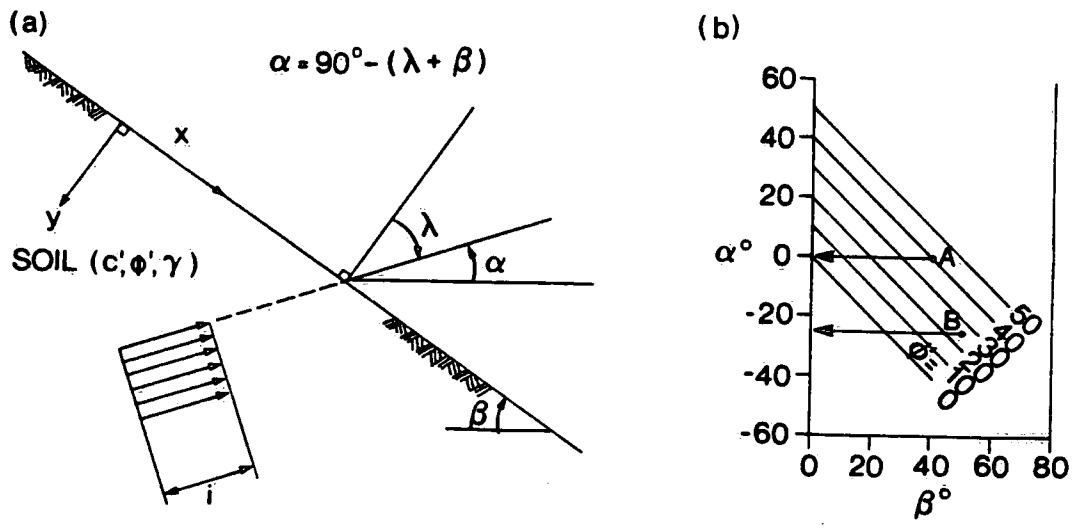

Figure 1. The influence of seepage direction on slope stability. a) Definition of the hydraulic gradient vector i and direction (after Iverson and Major, 1986). b) Case A - for a slope with β = 40° and ϕ' = 40°, the most adverse seepage direction is the horizontal one. Case B - for a slope with β = 50° and ϕ' = 25°, the most adverse direction is 25° below the horizontal.

PORT BURWELL

The method has been applied to the study site on the north shore of Lake Erie near Port Burwell, Ontario, where groundwater and pore pressures have been monitored over the period of seven years. Apart from occasional rotational slides, gully erosion due to groundwater seepage is an important failure mechanism of the bluffs. Fig. 2 shows a simplified stratigraphic cross section with a represenative position of the phreatic surface and measured pore pressures. The section is subdivided into finite elements (Fig. 3) and the analysis is performed both for the isotropic and anisotropic coefficients of permeability. Of special interest are the hydraulic gradients computed at three exit nodes (Nos. 56, 72 and 89) located on the bluff face.

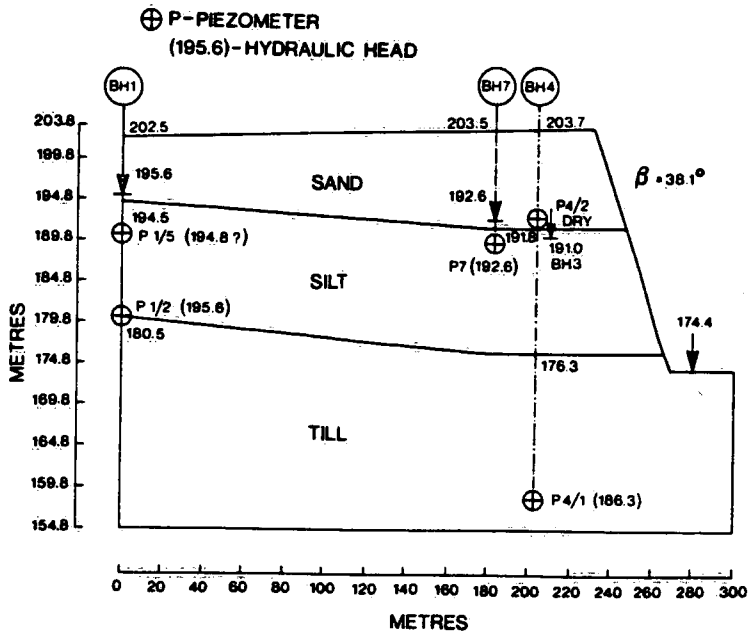

Figure 2. Simplified stratigraphic cross section with measured hydraulic heads.

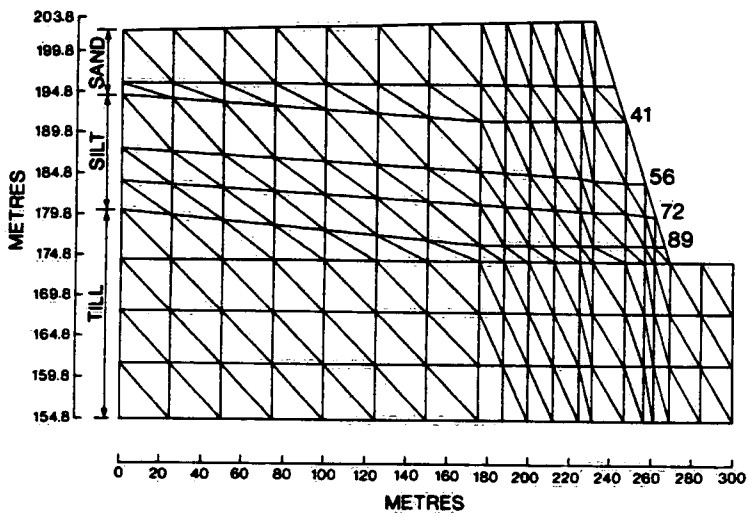

Figure 3. Finite element mesh showing four exit nodes at the surface of the silt stratum.

The effect of anisotropic permeability within the sensitive silt stratum was investigated and the best agreement between the measured and computed hydraulic heads was obtained for the values $k_h = 5 \times 10^{-4}$ cm s^{-1} and the k_h/k_v ratio of 50, where k_h and k_v are the average horizontal and vertical

permeability coefficients respectively. The local factors of safety against seepage erosion F are defined as the ratios of the critical hydraulic gradient i_{cr} and the hydraulic gradients i obtained from the FEM analyses for the same orientation of the seepage gradient vector. The computations of the factors of safety (Table 1) suggest that both cohesion and anisotropic permeability are required to prevent gully erosion at the interface between the silt and till layer (Node 89, Fig. 3). The results are in agreement with field observations that no gully has formed at this location over the period of six years.

TABLE 1

Factors of Safety Against Seepage Erosion

	Nodes (Fig.3)		
	56	72	89
(a) isotropic permeability, $k = 5 \times 10^{-5}$ cm s^{-1}, silt cohesionless			
F =	0.15	0.09	0.09
(b) anisotropic permeability, $k_h = 5 \times 10^{-4}$ cm s^{-1}; $k_h/k_v = 50$, silt cohesionless			
F =	4.03	0.47	0.27
(c) isotropic permeability, k as in (a), silt cohesive			
F =	1.55	1.05	0.89
(d) anisotropic permeability, k_h and k_h/k_v as in (b), silt cohesive			
F =	41.43	4.82	2.79

PORT GRANBY

The second case history is concerned with seepage erosion occurring in 30 m high bluffs at the Waste Management Facility (Fig. 4) located at Port Granby, Ontario, on the north shore of Lake Ontario. The site has been used for the disposal of chemical and low-level radioactive waste since 1954. The main topographic features within the site are two gullies (the east and west gorges in Fig. 4), which have formed due to erosion from surface runoff and groundwater seepage. The gullies have been partially filled with the waste

material and the waste has been also stored in dug-out trenches at the top of the bluffs. The major concern at present relates to the effects of continued seepage erosion at the interface between a relatively pervious silt layer, which is underlain by a relatively impervious clayey silt till (Fig. 5). Seepage problems have ben recognized at the site in the late seventies and the site has been closely monitored since then.

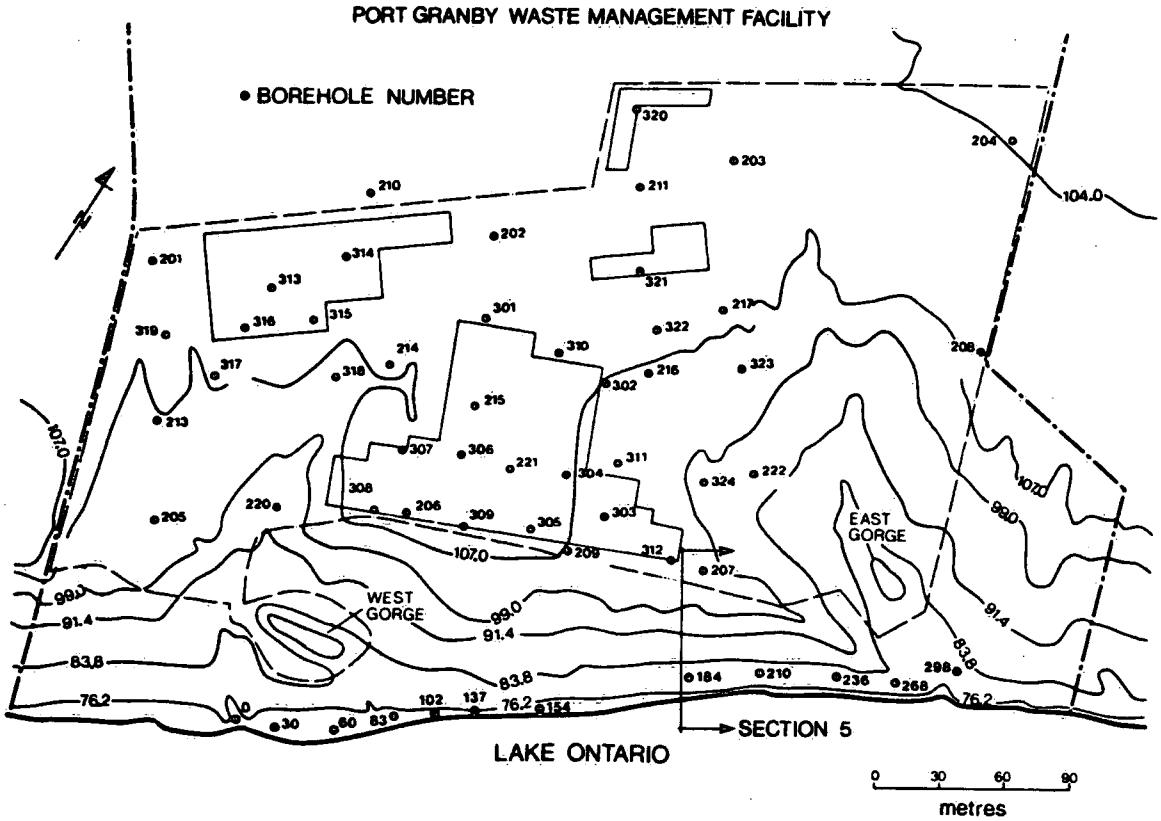

Figure 4. The general plan of the Port Granby waste management site (after Bobba and Joshi, 1988).

The corresponding finite element mesh of the section is shown in Fig. 6. Using the measured groundwater conditions and anisotropic permeability coefficients, orientation of seepage vectors can be determined (Fig. 7). The local factor of safety at the critical node 24 is computed using measured strength parameters for the sensitive silt stratum. The analysis (Fig. 8) indicates that the factor of safety of unity is obtained for the local slope angle of about 35°, which is in agreement with site observations.

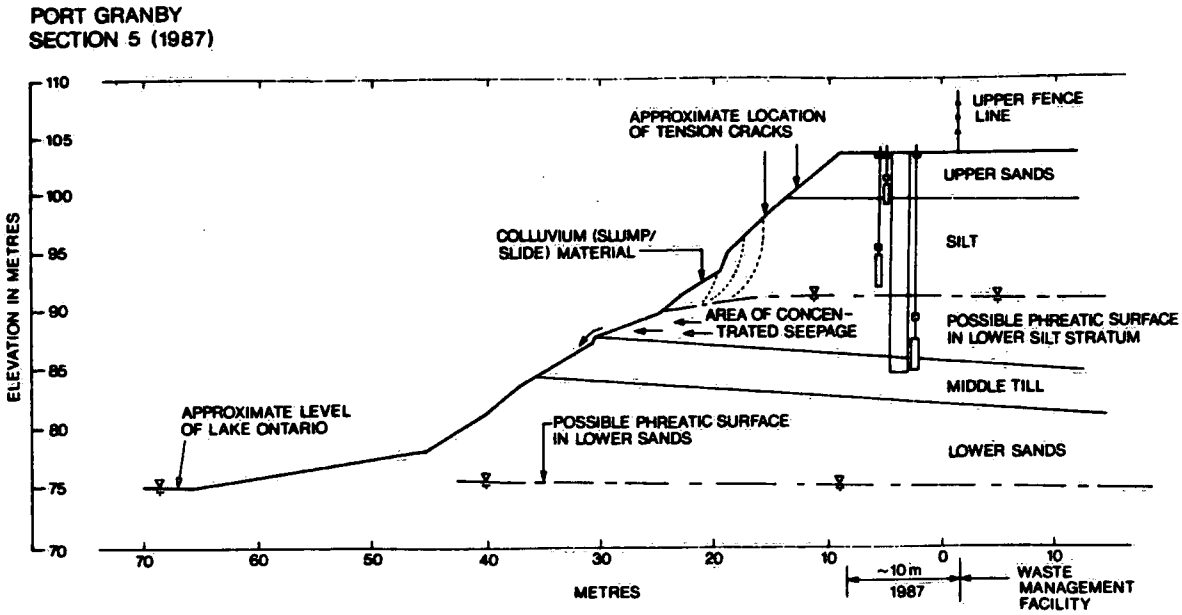

Figure 5. Bluff stratigraphy at Section 5 (after Golder Associates Ltd., 1988a).

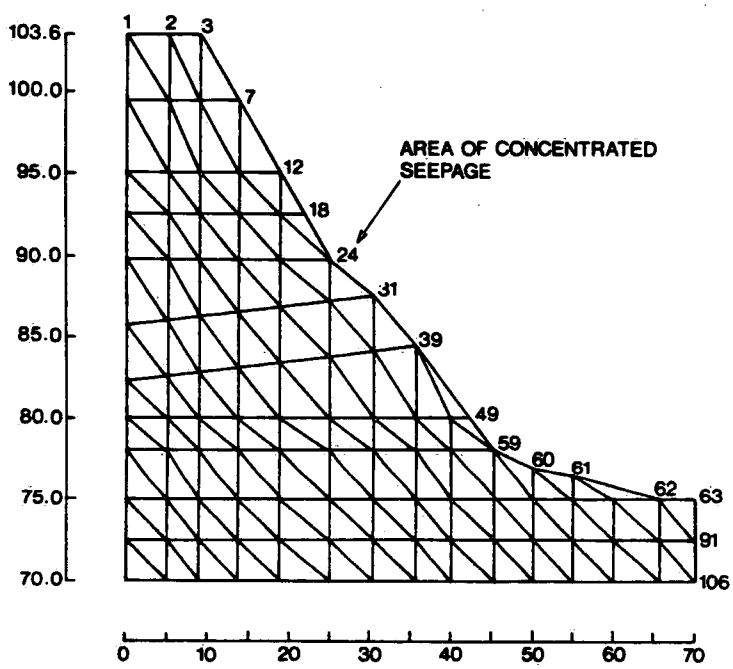

Figure 6. Finite element mesh of Section 5.

REMEDIAL DEWATERING MEASURES

The monograph by Cedegren (1977) provides an overview of commonly-used stabilization methods of natural soil slopes by means of artificial drainage. In principle, three methods are applicable to the problems of stabilizing high shore bluffs: (a) surface drainage trenches and blankets; (b) vertical well systems; and (c) horizontal drains.

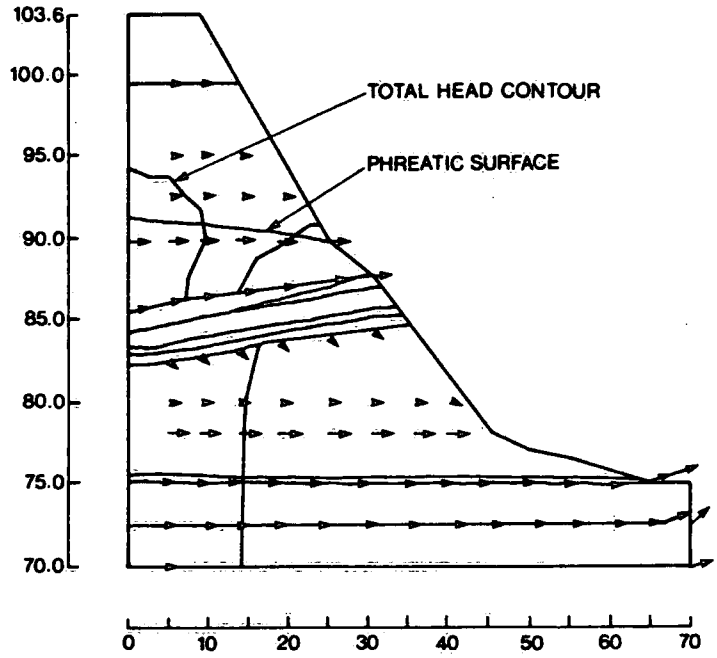

Figure 7. Groundwater flow pattern at Section 5. Arrows represent computed velocity vectors at each node.

The first method has been proposed for stabilization of ravines along the Scarborough Bluffs (Geocon, 1984). Extensive remedial measures, including granular fill dumped from the crest of the slope, a main gully drain with counterforts, a toe drain and subsurface finger drains through a foreshore platform have been recommended in the preliminary design for the stabilization of rapidly-retrogressing Sunnypoint Ravine.

Vertical wells are used to improve seepage erosion caused by perched groundwater. Sand-filled wells (sand drains) provide permanent lowering of the water table. Hutchinson (1982) gives an account of a stabilization scheme of 35 m high cliffs in England where seepage erosion has been stopped by a double row of vertical 20 cm diam. sand drains located 15 to 25 m behind

the unstable cliff face. For the temporary lowering of the groundwater table, eductor wells are used. This approach, using 25 eductor wells, installed on 2.5 m centres, together with the construction of a filter/drainage system, has

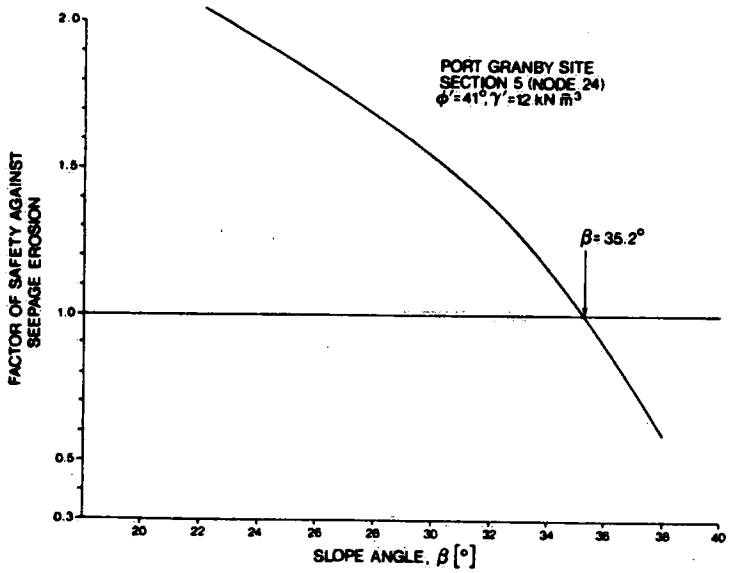

Figure 8. The relationship between the slope angle and the factor of safety against seepage erosion at Section 5.

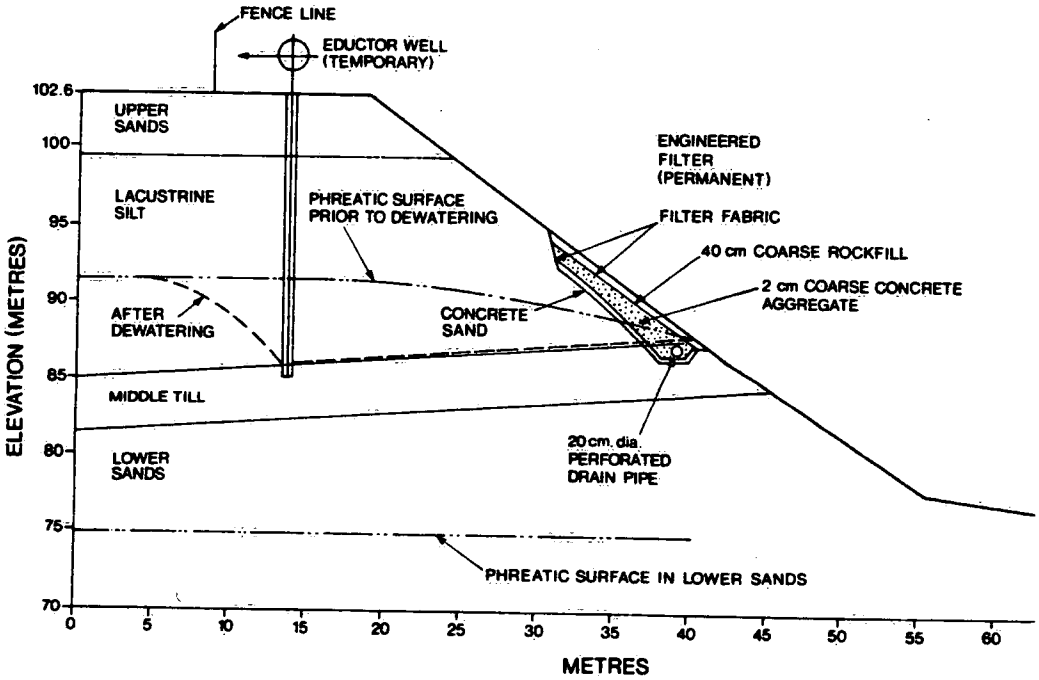

Figure 9. Dewatering system installed at Section 5 (after Golder Associates Ltd., 1988b).

been adopted for the demonstration stabilization at the Port Granby site (Fig. 9).

Horizontal drains are usually small-diameter wells drilled horizontally at the toe of the slope or they are installed at several levels. Nonveiller (1970) analyzed the effect of horizontal drain installation on the overall improvement of the factor of safety and showed that the improvement in safety of approximately 30 percent can be achieved. Kenney et al. (1977) used laboratory seepage tests and limit equilibrium calculations to present design charts concerning the choice of drain length and drain spacing. The charts are applicable to homogeneous slopes having inclinations from 16° to 22°. For two slope configurations studied, an improvement in stability in the order of 25 percent was predicted. According to the authors, for steeper slopes the charts underestimate the stabilizing influence of the drains. Both of these studies analyzed the improvement in stability against rotational failure using the well-known Bishop method for circular rotational surfaces (Bishop, 1955).

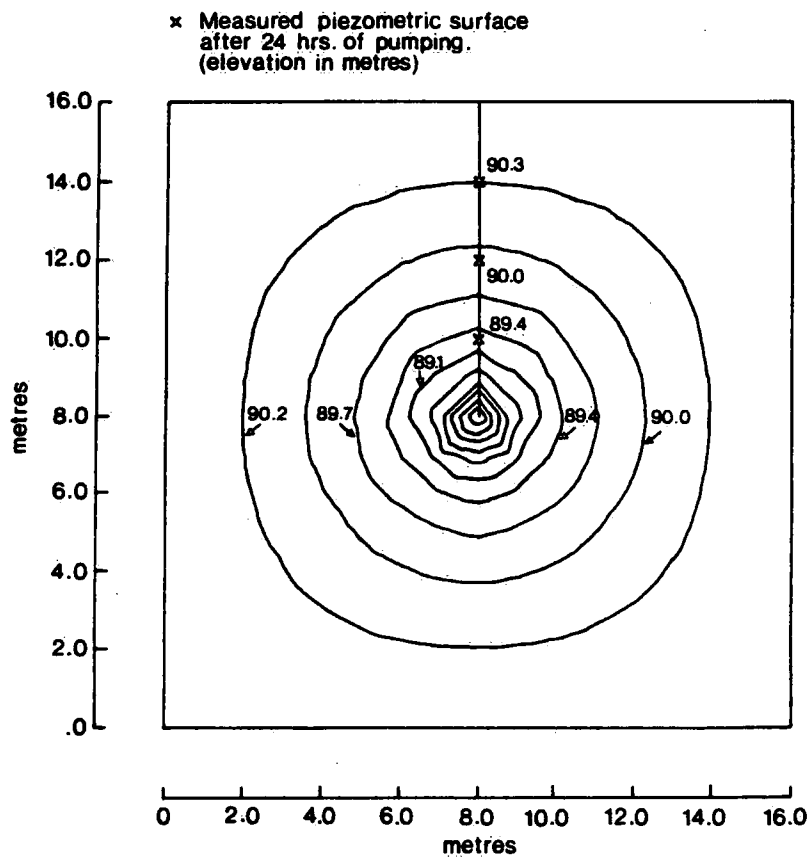

Figure 10. Predicted piezometric surface for the eductor well at Section 5, k = 2.3 x 10^{-5} cm s^{-1}, compared with measured values.

Using the finite element seepage analysis, it is possible to evaluate the design and efficiency of proposed dewatering systems. The analysis yields hydraulic gradients at seepage-face locations, which then permit computations of safety factors against seepage erosion. In two-dimensional analyses, different permeability of drains and filters can be easily incorporated to predict hydraulic-head distribution and water table configuration. The axisymmetric seepage analysis permits to analyze flow into vertical wells. The efficiency of eductor wells can be predicted using a plan view analysis (Fig. 10). The finite element seepage analysis thus provides a versatile and comprehensive tool in the design of dewatering systems for high shore bluffs.

CONCLUSIONS

The present paper leads to the following conclusions:

1. Seepage erosion, with considerable destructive potential, is widespread along the bluff-type shoreline of the lower Great Lakes. Strata consisting of glaciolacustrine silts are particularly prone to seepage erosion due to small particle size and very low cohesion.

2. Limit equilibrium methods, used to determine the factor of safety against rotational or planar sliding, do not adequately represent the loss of stability caused by seepage erosion and limit equilibrium computations may therefore lead to completely erroneous results.

3. Stability against seepage erosion depends on slope geometry, hydrodynamic forces and soil geotechnical properties. Local factors of safety against seepage erosion can be obtained from the finite element seepage analysis and the results of geotechnical tests. The lowest factors of safety are usually determined at the interface of two strata with different permeability.

4. For the two site-specific cases examined, steady-state analysis proved to be adequate. Transient analysis is likely in order for cases where phreatic surface is close to the ground surface or the seasonal fluctuation of groundwater seepage is substantial.

5. The design and effectiveness of proposed dewatering remedial measures can be easily incorporated into the FEM seepage analysis.

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