

EFFECT OF PORE FLUID CHEMISTRY ON THE TRIAXIAL BEHAVIOUR OF A HIGH PLASTIC CLAY

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ABSTRACT Recent studies conducted on the clay foundation of a dyke revealed significantly different pore fluid chemistry, soil properties and triaxial behaviour between a stable and an unstable section of the dyke. Chemical analysis of the pore fluid from the foundation clay at the stable section, unstable section and a background section that carried no dyke showed notably lower concentrations of calcium, magnesium and sulphate beneath the dykes relative to the background section. This suggested depletion of gypsum by leaching due to seepage beneath the dykes. The unstable section was observed to be more brittle and more anisotropic than the stable section. The results suggested that the foundation clay contained cementation bonds that were being weakened by leaching beneath the dyke and then broken by shear straining.

The loss of calcium by groundwater leaching appears to have increased the Na/Ca ratio for specimens from beneath the dykes relative to the background section. This represents a relative decrease in electrolyte valence in the pore fluid beneath the dykes. Increased Na/Ca ratios and lower electrolyte concentrations increase the diffuse double layer (DDL) thickness. These changes can produce increased interparticle repulsion, increased water content, and a decrease in interparticle contact stress for a constant total stress. All of these processes result in a weaker soil and lower stability of the dyke.

Introduction

Variations in properties and behaviour of high plastic clay over a range of environmental conditions are of major importance in geotechnical engineering for geoenvironmental applications. Changing pore fluid chemistry is one of the environmental conditions that can occur within the lifetime of many engineering projects.

Plastic clays with high montmorillonite contents are frequently used in geotechnical and geoenvironmental applications as barrier material for the control of groundwater flow and containment of contaminants. Changes in pore fluid chemistry can be caused by groundwater leaching and contamination from the material being contained. These changes need to be considered to ensure continued long-term performance of the original design. Several examples of applications where changes in pore fluid chemistry can be a factor are listed below:

- Clay barriers for containment cells and lagoons, land fill liners and hazardous and nuclear waste isolation;
- Embankment, dam and natural slope stability including clay cores and foundations of water retention and tailings dykes; and
- Non-aqueous phase liquid contamination and *in situ* containment of contaminated sites.

Depending on the specific application, different changes in pore fluid chemistry can be expected and each may have different effects on soil properties and behaviour. A common mechanism for changing pore fluid chemistry is seepage of water from a reservoir or retention pond through or under a retaining structure. The changes can involve either decreases or increases in pore fluid concentrations.

Changes in pore fluid chemistry have been identified as probable causes of changes in soil properties such as strength, compressibility and hydraulic conductivity. Reduced pore fluid electrolyte concentrations, elevated monovalent/divalent cation ratios and dissolution of cementation bonds can result from leaching by relatively fresh ground water. These chemical changes can weaken a soil by increasing the diffuse double layer thickness and hence increasing repulsive forces. As such, these changes need to be considered to ensure continued long-term performance of the original design.

This paper discusses the basic physicochemistry of soils and the relationship between pore fluid chemistry and interparticle stress. It then presents a case study from Eastern Manitoba in which ground water leaching beneath a water retention dyke resulted in changes in pore fluid chemistry. These changes, are then related to the triaxial behaviour of the high plastic montmorillonitic foundation clay.

Physicochemical Effects on Soil Mechanics

The geotechnical properties and behaviour of clay soils are controlled by mineralogy, interparticle forces, soil structure and the physicochemical interactions between adjacent clay particles. Changes in pore-fluid chemistry can influence physicochemical interactions between the clay particles and subsequently influence the overall geotechnical behaviour of the soil (Barbour and Yang, 1993).

Montmorillonitic clays like the foundation clay in the case study contain 2:1 clay minerals in which basic units consist

of an aluminum octahedral sheet sandwiched between two silica tetrahedral sheets. A layer of water and ions is located between two basic montmorillonite clay particles. The bond between two adjacent clay particles is relatively weak and can change thickness with changing water content and pore-fluid chemistry. Montmorillonitic clays have high plasticity index and swelling potential.

Isomorphous substitution of aluminum for silicon in the tetrahedral sheets and/or magnesium for aluminum in the octahedral sheets results in a net negative charge on the clay particle surface. The negatively charged surface attracts cations and repels anions dissolved in the pore-fluid. The combination of the charged surface and the distributed charge in the liquid phase is known as the diffuse double layer (DDL) (Mitchell, 1993).

The relation between electrical potential within the DDL and distance from the clay particle is given by the Poisson-Boltzmann equation:

$$\frac{d^2\psi}{dx^2} = -\frac{4p}{D} \sum n_i z_i e \exp\left(\frac{-z_i e \psi}{kT}\right) \quad [1]$$

where ψ is the average electrical potential, x is the distance from the charged surface, D is the dielectric constant of the pore-fluid, n_i is the concentration of the i^{th} species in the pore-fluid, z_i is the valence of the i^{th} species, e is the charge of an electron, k is the Boltzmann constant and T is temperature (Yong *et al.* 1992). Equation [1] is most applicable to weak suspensions of clay particles in water, but has been found to be relevant also in many soft clays, specifically post-glacial clays. Equation [1] can be solved to obtain the thickness of the DDL for a given clay particle:

$$\frac{1}{K} = \sqrt{\frac{DKT}{8pnz^2e^2}} \quad [2]$$

where $1/K$ is the distance from the charged surface to a point in the pore-fluid where the electrical charge is balanced (Yong *et al.* 1992). Equation [2] shows the effects on the thickness of the DDL of changing pore-fluid chemistry, specifically dielectric constant of the pore-fluid, and the concentration and valence of dissolved solutes.

When two clay particles face one another, a repulsive force will result due to electrostatic repulsion of cations and the resulting potential fields from overlapping DDLs. Thicker DDLs result in higher repulsive forces for a given particle spacing. Concurrently, an attractive force will exist between the particles due to van der Waals forces. In general, repulsion is dominant. The repulsive and attractive forces can be integrated over a number of particles to get the net force on a unit section of the material. This has been termed the net long-range repulsive stress $|R - A|$.

Net long-range repulsive stresses contribute to the total effective stress of a soil, where a portion of the effective stress is carried by true physical contacts between soil particles and the remainder is carried by $|R - A|$. This can be written (Graham *et al.* 1992):

$$\{s'\} = \{s^*\} + \{|R - A|\} \quad [3]$$

where s' is the effective stress and s^* is the stress transferred between true physical contacts between soil particles, including friction and cementation bonds. Repulsion, which is largely controlled by pore fluid chemistry, can play an important role in controlling volume change and shear strength of active clay soils under controlled loading (Barbour and Yang, 1993; Mitchell, 1993).

Case Study

Water retention dykes at a hydroelectric generating station located in southeastern Manitoba have experienced ongoing slope instabilities. The dykes were initially constructed in 1929. In the late 1940s, the dykes were increased in elevation and length to raise the head on the power plant. Since then, instabilities have occurred irregularly on the dry side of the dykes at various sections. It should be noted that none of the instabilities has resulted in uncontrolled release of reservoir water. Currently the owner of the dykes (Manitoba Hydro) is being proactive in preventing further instability of the dykes and has constructed berms behind the dykes at various locations.

The dykes consist of a clay core beneath a rip-rap shell. Their average height is approximately 7.0 m and the width of the crest is approximately 4.3 m. The clay fill material extends to a depth of approximately 8 m below the crest and overlies highly plastic foundation clay left by proglacial Lake Agassiz. The clay contains localized nodules or accretions of white amorphous material that has been identified as gypsum (Baracos 1977). The percentage of clay size particles in the upper part of the foundation clay can approach 100%. Clay minerals account for between 67% and 81% of the total composition of Lake Agassiz clay. The clay size fraction consists of approximately 75% montmorillonite, 10% illite, 10% kaolinite and 5% quartz (Loh and Holt, 1974; Baracos, 1977). The remaining soil fraction consists primarily of silt-sized particles composed of limestone and dolomite (Baracos and Graham, 1980).

Studies conducted by Garinger *et al.* (2001, 2002) examined the stability of the dykes on the basis of laboratory results from samples of the dyke and foundation materials. Based on triaxial testing and pore fluid chemical analysis, the authors postulated that the foundation clay probably contained cementation bonding that could be removed by leaching or broken by shear straining.

This paper summarises the previous investigations and presents the results of subsequent testing and chemical analysis of the foundation clay. Comparisons have been made between two sections of the dyke: one (SS-036) that

Table 1. Results of Pore Fluid Chemical Analysis

Section	EI. (m)	EC ($\mu\text{S}/\text{cm}$)	pH	Na (mg/L)	Mg (mg/L)	Ca (mg/L)	Cl (mg/L)	SO ₄ (mg/L)	HCO ₃ (mg/L)	Na/Ca	SAR (meq/L) ^{1/2}	Gypsum IAP/K _{sp}
Unstable	267.7	772	8.1	62	71	30	6.4	243	130	1.80	1.41	0.13
Unstable	266.7	1370	8.2	104	114	112	11.2	720	117	0.81	1.65	1.45
Unstable	266.4	1340	8.2	102	108	113	10.3	708	104	0.78	1.65	1.44
Unstable	266	1650	7.9	116	131	172	10.0	972	88	0.59	1.62	3.01
Stable	267.8	546	8.2	26	58	28	3.0	153	113	0.81	0.65	0.08
Stable	267	1190	8.1	58	115	97	6.3	609	95	0.52	0.94	1.07
Stable	266.5	3520	8.1	148	159	164	14.3	2016	113	0.78	1.98	5.95
Stable	266	1810	8.1	74	159	220	10.5	1122	92	0.29	0.93	4.44
BKG	267.8	1460	8.0	64	160	125	1.4	870	85	0.44	0.89	1.95
BKG	266.8	3950	7.8	108	505	554	3.0	3360	55	0.16	0.80	33.59
BKG	266.6	4160	7.7	116	533	680	6.0	3750	64	0.15	0.81	46.01
BKG	266.2	4150	8.6	116	505	680	6.2	3660	61	0.15	0.82	44.91

BKG = Background section
EI. = Elevation
EC = Electrical conductivity

SAR = Sodium adsorption ratio = $\text{Na}^+ / [(\text{Ca}^{2+} + \text{Mg}^{2+})/2]^{1/2}$
IAP = Ion activity product
K_{sp} = solubility product constant

had experienced instability in 1994, and a second (SS-040) that has remained stable. A third area, away from the dykes, section SS-042, was used as a background section through clay that has not been subjected to loading or seepage due to dyke construction.

Analysis of Pore Fluid Chemistry

Specimens for pore fluid analysis were obtained from the highly plastic foundation soil at the unstable, stable and background sections. At each section, four specimens of pore fluid were extracted for analysis, the first being approximately 0.5 to 1 m below the top of the foundation layer. The other three specimens were then taken from between 1.5 to 2.5 m below the top of the foundation layer.

Pore fluid samples were obtained by extruding saturated paste samples through a 0.45 micron filter. The pore fluid specimens were analyzed for major ions including sodium Na⁺, calcium Ca²⁺, magnesium Mg²⁺, chloride Cl⁻, sulphate SO₄²⁻ and bicarbonate HCO₃⁻. Electrical conductivity (EC) and pH were also measured.

The dissolved metals were analyzed by flame atomic absorption spectrophotometry (APHA 3111:B, 1998). Anions including chloride and sulphate were analyzed by ferricyanide and methylthymol blue colourimetry, respectively (APHA 4500-Cl:E and APHA 4500-SO₄:F, 1998). Bicarbonate was measured by titration with 0.01N HCl (APHA 2320:B, 1998). Electrical conductivity was determined using a conductivity cell (APHA 2510:B, 1998) and pH was determined electrometrically (APHA 4500-H:B, 1998).

Table 1 includes results of the pore fluid testing, while Figures 1 to 6 show graphs of the major cation and anion concentrations *versus* elevation at each of the three sections. The results reveal significant changes in pore fluid chemistry beneath the dykes compared to the background section. They suggest three possible mechanisms that may be responsible for the observed instabilities.

- 1) Lower electrolyte concentrations beneath the dykes.
- 2) Lower electrolyte valence beneath the dykes.

3) Loss of gypsum cementation.

The EC results indicate significantly lower total electrolyte concentrations beneath the dyke relative to the background section. The most significant trends observed are the notably lower concentrations of calcium, magnesium and sulphate beneath the dykes relative to the background section (Figures 2, 3 and 5). The concentrations of these ions beneath the dykes are consistently lower than the background section throughout the entire profile. The difference is especially evident at elevations below 267 m. Worth noting is the broadly similar concentrations of the various ions at the stable and unstable sections. (The unstable section generally has concentrations just a little lower than the stable section, but significantly lower than the background section.) This is obviously a concern since it implies that the conditions at the stable section may be approaching those of the unstable section.

With the exception of bicarbonate, all of the ions were observed to increase in concentration with depth at each section. This is likely the result of downward leaching before construction of the dykes, followed by horizontal leaching after the construction of the dykes. A greater number of pore volumes can be expected to have passed beneath the dykes at higher elevations.

The loss of calcium and magnesium increases the monovalent to divalent cation ratio. That is, the overall valence of the electrolytes in the pore fluid decreases. This is indicated by both the Na/Ca ratio and the sodium adsorption ratio SAR presented in Table 1. The entire unstable profile shows Na/Ca ratios greater than the background range. The Na/Ca ratios at the stable section are generally less than the unstable section. However, the upper three samples of the stable section were greater than the background range.

The SAR is used to represent the relative concentrations of monovalent sodium to the divalent cations calcium and magnesium that are in the adsorbed complex. The proportion of sodium in the adsorbed layer is an important factor influencing the structural status of a soil (Mitchell,

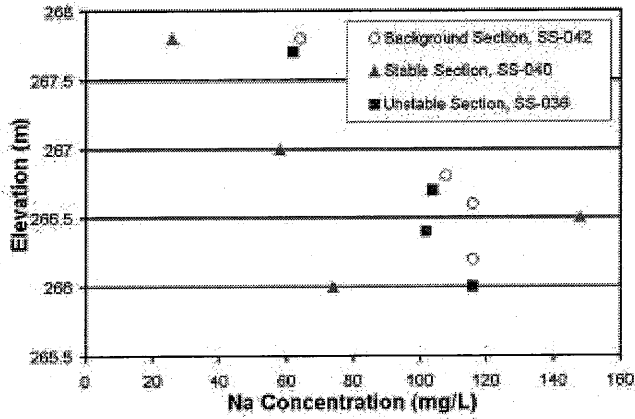


Figure 1. Sodium concentration vs. elevation

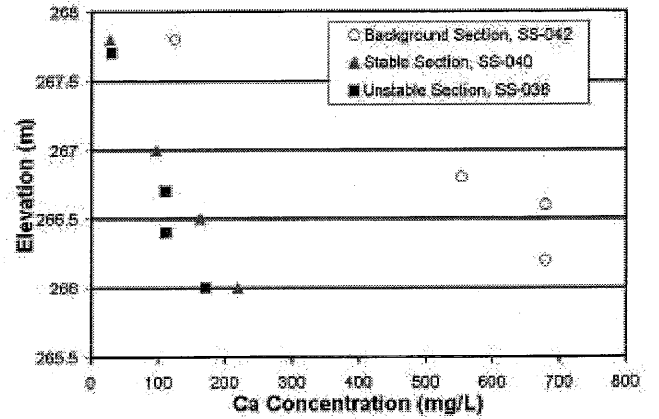


Figure 2. Calcium concentration vs. elevation

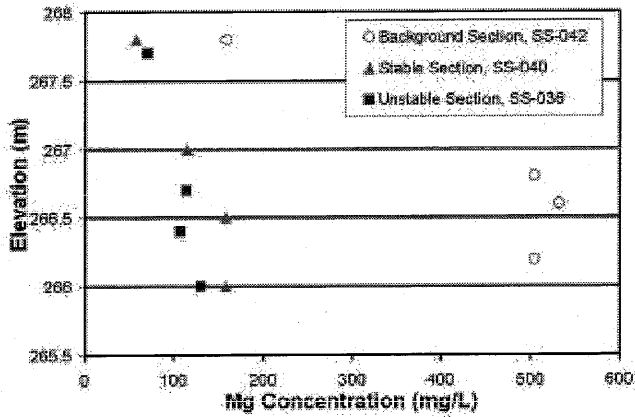


Figure 3. Magnesium concentration vs. elevation

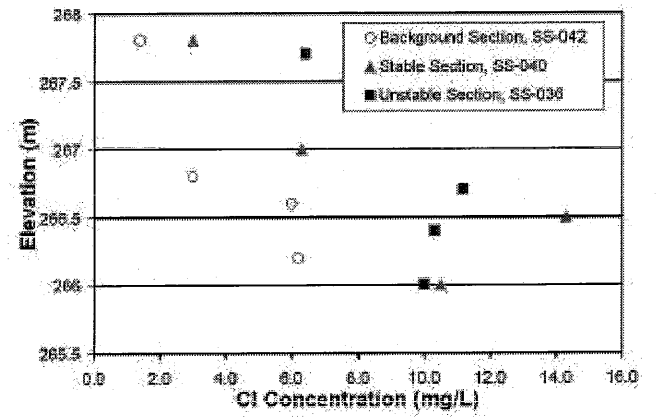


Figure 4. Chloride concentration vs. elevation

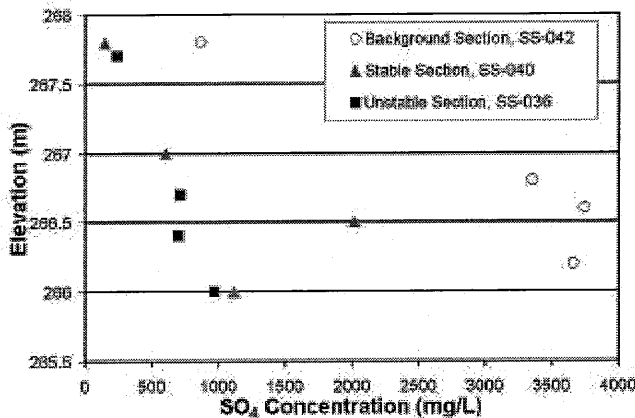


Figure 5. Sulphate concentration vs. elevation

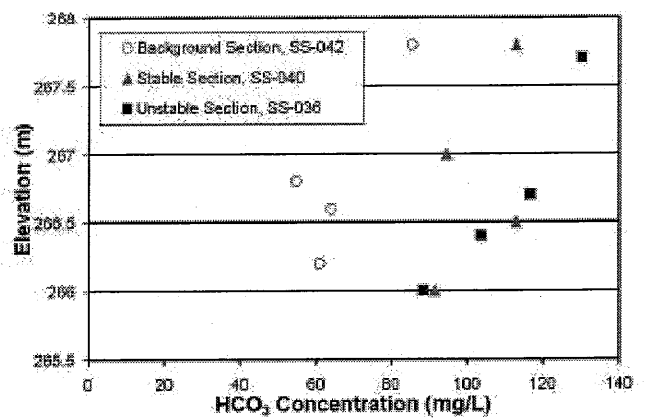
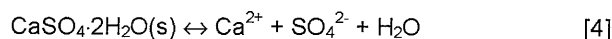


Figure 6. Bicarbonate concentration vs. elevation

1993). The values presented in Table 1 separate the unstable section from the stable and background sections. All of the samples in the unstable section revealed SAR values greater than 1 (meq/L)^{1/2} whereas the majority of the SAR values are less than 1 (meq/L)^{1/2} in the stable and background sections.

Less notable differences were observed for sodium, chloride and bicarbonate between the three sections (Figures 1, 4 and 6). The similarity in bicarbonate concentration between the three sections suggests that carbonate leaching, and therefore loss of carbonate cementation, is not a factor.

The lower concentration of calcium and sulphate in the pore fluid in the foundation clay beneath the dyke suggests diminution of gypsum (CaSO₄·2H₂O) beneath the dykes with time. The equilibrium reaction for gypsum dissolution is :



The ion activity product (IAP) was calculated for each specimen using the Law of Mass Action for equation [4]:

$$[\text{Ca}^{2+}][\text{SO}_4^{2-}] = \text{IAP} \quad [5]$$

The IAP can then be compared to the solubility product constant (K_{sp}) to estimate whether the pore fluid is undersaturated, at equilibrium or supersaturated with respect to gypsum.

Table 1 presents values of the ratio of IAP to the K_{sp} for gypsum ($\times 10^{-4.6}$ at 25°C). IAP/ K_{sp} values greater than unity, equal to unity and less than unity indicate supersaturated, equilibrium and undersaturated conditions, respectively. At the unstable section, the top sample was undersaturated, the next two samples were approximately at equilibrium and the bottom sample was supersaturated. A similar pattern was observed at the stable section where the top sample was undersaturated, the next sample was approximately at equilibrium and the bottom two samples were supersaturated. In contrast, all of the samples from the background section were supersaturated to highly supersaturated.

Based on these results, pore fluid conditions at the background section and the two sections beneath the dyke were significantly different. Specifically, pore fluid concentrations are lower beneath the dykes, the Na/Ca ratios are greater beneath the dykes and the change in chemistry suggests a reduction in gypsum cementation beneath the dykes. This suggests that the flow of water beneath the dykes is affecting the pore fluid chemistry. Testing is now being done specifically to investigate the effect of these changes in chemistry on the mechanical properties of the clay at Seven Sisters. It is known however (Barbour and Yang 1993) that changes in pore fluid chemistry like those in Table 1 do change the thickness of diffuse double layers and will therefore affect compressibility, strength, and hydraulic conductivity of the clay.

Geotechnical Testing Program

Specimens were obtained from the highly plastic foundation soil at the unstable, stable and background sections for geotechnical testing. In addition to traditional classification by hydrometer and Atterberg limits, the laboratory program included isotropically consolidated undrained (CIU) triaxial tests. Four specimens of the high plastic foundation clay were tested from each section.

Atterberg limits performed on the foundation soil resulted in liquid limits ranging from 100 – 120% and plastic limits from 30 – 45% at the unstable section. At the stable and background sections liquid limits ranged from 80 – 117% and plastic limits from 20 – 35%.

Hydrometer tests on the foundation soil showed the clay size fraction as being near 100% in the foundation at the unstable section. At the stable section it was 95% in the upper part of the foundation, reducing to 72% one metre below. This confirmed visual observation of more silt in the foundation at the stable section relative to the unstable section.

Figures 7 and 8 show results of CIU triaxial tests for the unstable and stable sections, respectively. Results obtained from the background section are presented on both plots for comparison. The pressures shown in the figures represent the effective confining stress used for each test. All specimens were taken from elevations of 267.7 to 265.5 m, that is, in the high plastic clay under the dyke.

The tests indicate strain softening stress-strain behaviour, with peak strengths being reached at 1 to 4% strain. The figures show that softening of specimens from the unstable section is generally steeper than at the stable and background section.

Based on lines connecting approximate 'post-peak' (or 'normally consolidated') points on deviator stress vs. mean effective stress plots at axial strains of about 4% in Figures 7 and 8, ϕ' was found to be approximately 13° in the foundation clay of the unstable section, 14° at the stable section and 12° at the background section. These are very low values of ϕ' that correspond to rather poorly defined 'post-peak plateaus' in the q vs. ϵ_1 diagrams. The plateaus represent a limited period of constant shearing resistance.

Following the post-peak plateaus some tests showed a further reduction in deviator stress with additional axial strain and the development of well-defined failure planes. When failure planes developed, they first appeared quite early in the tests, between 1% and 6% axial strain. After the tests ended, the failure planes were separated and examined. They were generally shiny and slickensided. The lowest shearing resistance in the tests has been interpreted as residual strength, even though it is unusual to reach residual conditions in triaxial tests. Connecting the lowest deviator stresses in the q vs. p' plots in Figures 7 and 8 and assuming no cohesion, the residual friction angle ϕ'_r was found to be 10.3°, 10.7° and 10.6° for the unstable, stable and background sections, respectively.

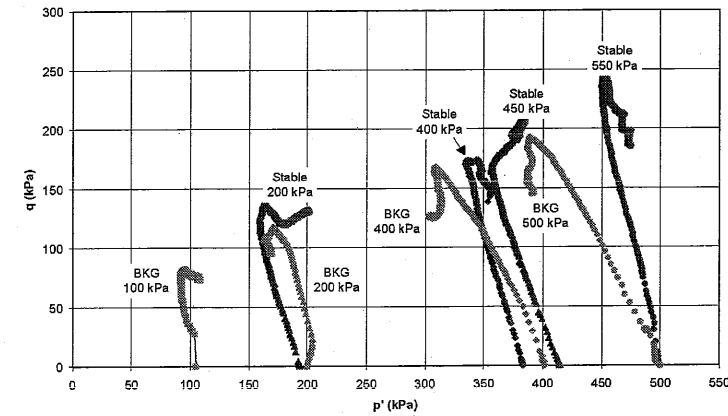
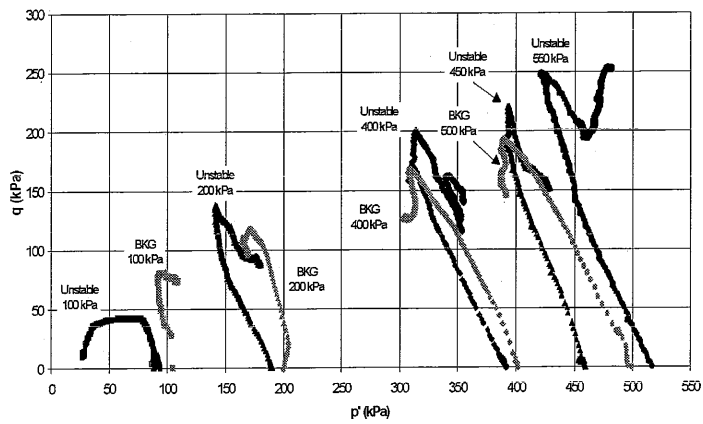
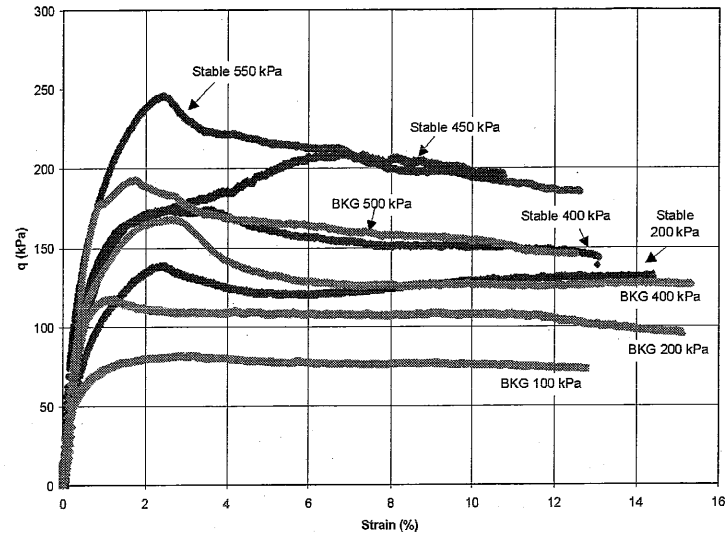
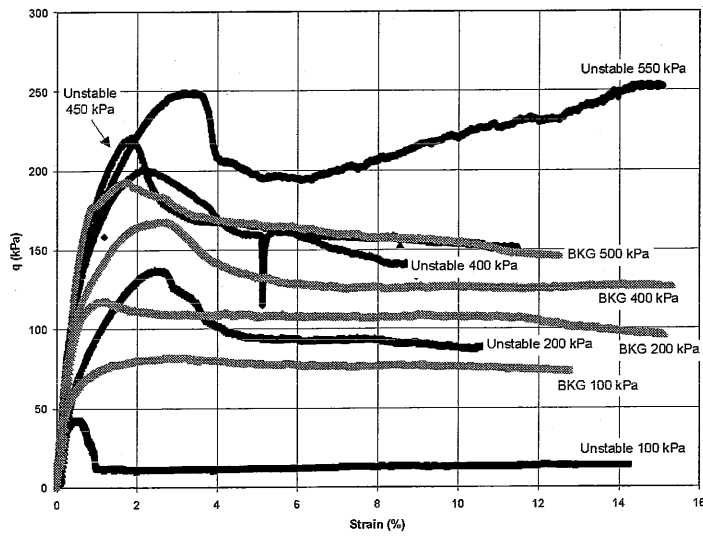


Figure 7. CIU triaxial test results from the unstable section (black) compared to the background section (light grey).

Figure 8. CIU triaxial test results from the stable section (dark grey) compared to the background section (light grey).

The lower plots of Figures 7 and 8 show deviator stress q , vs. mean effective stress p' . Table 2 shows values of $\Delta p'/\Delta q$ in the linear sections of these graphs. The stress paths are further from the vertical at the unstable section than at the stable section, indicating greater anisotropy at the unstable section. This shows that at the same stress state, the unstable section can generate higher excess pore water pressures than the stable section. At early stages in the tests, the specimens from the background section followed similar $\Delta p'/\Delta q$ ratios as the stable section. Unexpectedly, at later times in the tests, the stress paths bent towards $\Delta p'/\Delta q$ ratios similar to the unstable section. Further testing is required to determine the cause of this observation.

Table 2. $-\Delta p'/\Delta q$ ratios.

Isotropic Consolidation Pressure	Unstable	Stable	Background Early	Background Late
100 kPa	0.38	-	0.17	-
200 kPa	0.53	0.31	0.26	-
400 kPa	0.50	0.27	0.34	0.56
450 kPa	0.43	0.38	-	-
500 kPa	-	-	0.31	0.50
550 kPa	0.45	0.25	-	-
Average	0.46	0.30	0.27	0.53

Discussion and Conclusions

Slope stability analysis of the site was reported by Garinger et al, 2002. When post-peak strengths were used in slope stability analyses, the solutions lead to the conclusion that the unstable and stable sections do not fail. When residual strengths were used, both sections fail. Other processes have to be examined if instability is to be identified.

The brittle and possibly cemented structure observed in the triaxial tests and the results of the pore fluid chemical analyses suggest that the pore fluid chemistry in the high-plastic clay may have been altered due to slow seepage of the water from the forebay through the foundation soil in a normal response to potential differences across the dike. The rates at which this seepage takes place will be affected by the irregular sand or silt partings that are seen in all lacustrine clays.

The concentrations of calcium and sulphate measured at the background section indicate that the pore fluid was strongly supersaturated with respect to gypsum. Under supersaturated conditions, gypsum precipitation would be expected, as was observed in the field, and would result in cementation of the soil.

Gypsum is soluble in water and can be readily leached as relatively fresh reservoir water flows through the dyke foundation. This is reflected in the electrical conductivity (EC) data, where significantly lower EC was measured in the pore water samples extracted from beneath the dyke. As indicated by Equation [2], lower ion concentrations result in an increase in DDL thickness.

The elevated Na/Ca ratios and SAR values measured at the unstable section (Table 1) indicate a relatively greater proportion of sodium and a corresponding lower overall valence of the pore fluid at the instable section. Based on Equation [2], this can also result in an increase in DDL thickness. The SAR provides a good indication of the stability of non-marine clay soil structure and resistance to breakdown and particle dispersion (Mitchell, 1993).

Based on this understanding, three factors could be contributing to the instability of the dykes. Lower electrolyte concentrations and valence can increase the DDL thickness, which translates to increased interparticle repulsion, increasing water content, and a decrease in interparticle contact stress for a constant effective stress (Equation [3]) thus resulting in a weaker soil. The loss of cementation bonding appeared to change the brittleness of the soil.

The specimens were clearly strain softening, suggesting an overconsolidated, cemented, or 'structured' material. The morphology of the site is such that there has never been historical loading followed by unloading. Any apparent preconsolidation pressures will therefore be due to desiccation effects, former changes in ground water level at times of drier climate in the period since deposition, or some form of cementation. Maximum shearing resistance came at relatively small axial strains, often in the range 1 – 3%. The friction angles were similar between the three tested sections. However, the foundation clay in the unstable section generally softened more quickly with strain than the

clay in from the stable and background sections. The steepness of the reductions in shearing resistance in some of the graphs suggests a brittle, possibly cemented, microstructure and this has been seen in some other test programs on Lake Agassiz clay (Baracos 1977, Graham et al.1983).

Removal of gypsum cementation by leaching can create a more brittle soil similar to what was observed in comparing Figures 7 and 8. It seems likely that the cementation was maintaining a quasi-stable soil structure that reflects the depositional conditions. For example, this initial structure may consist of some flocculated edge to face contacts. Upon straining of the soil, the quasi-stable structure will be destroyed, causing the observed strain softening behaviour. If any cementation at the interparticle contacts is lost, the soil structure will more readily yield and the soil will display a higher degree of strain softening.

The q vs. p' plots (Figures 7 and 8) show that the upper foundation clay beneath the dyke has remarkably linear behaviour until quite close to failure, with the soil from the unstable section being more anisotropic (and possibly more brittle) than the stable section. (Graham and Houlsby 1983 related the slopes of q vs. p' plots to anisotropy of the material.) The greater anisotropy of the material at the unstable section will produce larger pore water pressures as the material moves towards shear failure, and therefore lower undrained shear strengths for a given consolidation pressure. Further testing is required to examine the change in slope observed at the background section.

Acknowledgements

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