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Soil Behaviour in the Stability Evaluation of a Half-Century-Old Hydraulic Fill Dyke

by

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A thesis submitted in conformity with the requirements
for the degree of Master of Applied Science
Graduate Department of Civil Engineering
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Abstract

The purpose of this study is to analyze the impact that reservoir filling may have on a dyke known as Cacara 2 which is owned and operated by Light SESA in Rio de Janeiro, Brazil. Dyke 2 was built in 1945 according to the hydraulic fill method to close off a low topographical area to create the "Lajes Reservoir," part of the Lajes Hydroelectric and Water Supply Project. Plans are being made to raise the reservoir level 3 meters above the existing operational level to improve the hydroelectric and water supply capacities of the Lajes reservoir. The dyke is made up of thin interbedded clayey silt layers which cross the dyke's mass in an upstream-downstream direction. The focus of this study is to analyze the properties and behaviour of the soil in one of these layers. This layer, which has been above the reservoir level for over 50 years, will be subjected to the effects of reservoir filling and drawdown (wetting-drying). The main concern is in regard to internal erosion during reservoir filling, because the layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts. The dominant clay mineral is Na-kaolinite, which is a residual clay derived from gneiss; and it ranges from dispersive to non-dispersive. Tests carried out by the author on this Na-kaolinite at two different salinities, showed that the in situ soil fabric is characterized by an assemblage of positive edge-negative face flocculation, which was ascertained from the relationships among the liquid and shrinkage limits and sediment volume values and by way of permeability tests. These results substantiate the view that the lower the total dissolved salts in the reservoir water, the greater the susceptibility to deflocculation and internal erosion of this Na-kaolinite. In addition, results obtained by the Toluene Displacement Tests showed that upon water immersion this soil may lead to dispersion, which increases its susceptibility of deflocculation and internal erosion. This soil has no tendency for self-healing as shown by sediment volume tests. Internal erosion of this Na-kaolinite may occur in areas of high crack potential, at the contacts between zones with incompatibilities of stress, strains and deformations, and in areas of desiccation.

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Table of Contents

Abstract	ii
List of Figures	vi
List of Table	vii
1 Introduction	1
1.1 Introduction to the Case Study	1
1.2 Outline of the Thesis	2
2 Experimental Program	5
2.1 Background Information	5
2.2 Laboratory Tests	6
3 Discussion of the Results	29
3.1 Atterberg Limits	29
3.2 Pore-water pH	31
3.3 Cementing Agents	31
3.4 Shrinkage Factors	32
3.5 Volumetric Changes During Air Drying	33
3.6 Determination of Clayeytness Degree	34
3.7 Classification of Expansive Soils According to Sediment Volume	35
3.8 Identification of Dispersive Clays	36
3.9 Permeability Test Using the Triaxial Cell Apparatus	38
4 Conclusions	40
References	45

List of Figures

Chapter 1

Fig. 1.1 Cross Section of the Hydraulic Fill Dyke Studied	4
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Chapter 2

Fig. 2.1 X-Ray Diffraction of the kaolinitic soil	8
Fig. 2.2 X-Ray Diffraction of the kaolinitic soil	9
Fig. 2.3 Plasticity and Mineralogy Charts	17
Fig. 2.4 Potential Dispersiveness Chart (SAR)	23
Fig. 2.5 Potential Dispersiveness Chart	24

List of Tables

Chapter 2

Table 2.1	Physico-Chemical Characteristics of the Soil Studied	7
Table 2.2	Some Physical Properties of Intact Specimens at Two Different Salinities and pH Values	11
Table 2.3	Some Physical Properties of Remolded Specimens Using Bouth Deionized and NaCHO ₃ Pore Water Including Drying and Wetting Cycles	12
Table 2.4	Shrinkage Factors of the Soil Studied According to the Wax Method	13
Table 2.5	Determination of Clayeyiness Degree	15
Table 2.6	Volumetric Changes in Kaolinitic Residual Soils upon Air Drying	16
Table 2.7	Sediment Volume Method and Free-Swell Technique	19
Table 2.8	Expansivity Classification	20
Table 2.9	SCS Double Hydrometer Test	21
Table 2.10	Volumetric Changes Related to Length of Saturation Time	22
Table 2.11	Permeability Test on Thin Interbedded Kaolinitic Layer	26
Table 2.12	Physico-Chemical Characteristics of the Lajes Reservoir's Water Before and After Seepage Through the Foundation of the Dike	27

Dedicated to my son, Fernando. . . with love.

1 - Introduction

This research study seeks to predict the impact reservoir filling may have on a dyke called Cacaria 2 located in the City of Rio de Janeiro, Brazil, which is owned and operated by Light SESA. The focus of the study is to analyze the properties and behaviour of one of the thin interbedded clayey silt layers, which transversely cuts the dyke's mass in an upstream-downstream direction (See Fig 1.1). The main concern is in regard to internal erosion during reservoir filling, because the layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts. Furthermore, this soil range from dispersive to non-dispersive, and its volumetric changes may lead to the formation of cracks, which is a precursor to erosion.

1.1 Introduction to the Case Study

This case study involves an earth dyke named "Cacaria Dyke 2" built in 1945 in the State of Rio de Janeiro, Brazil. Dike 2 was built according to the hydraulic fill method to close off a low topographical area to create the "Lajes Reservoir" which is part of the Lajes Hydroelectric and Water Supply Project. Since its construction the dyke has exhibited numerous seepage and water-related problems. The dyke is 122 m long, 21.5 m high and has a crest elevation of 435 m above MSL (Mean Sea Level). The dyke was originally intended to be a conventional zoned earth fill containing a 70-to-80 % clay core, and flanked by pervious abutments composed of a 60-to-70 % sandy soil content. However, soil investigations conducted by Light in 1950, 1970, and 1991 showed that the expected zoning was not achieved. On the contrary, because it was not possible to carry out the original design of the dyke as planned,

alternating thick layers of high-permeability sandy soil and thin layers of low-permeability clayey silt soil had been formed. There is no discernible core.

As of 1950, the stability of the dyke has become primary concern for the following reasons: 1) the heterogeneity and layered nature of the soils used in the dyke has resulted in severe seepage; 2) the downstream area of dyke 2 has become saturated with water and serves as an exit point for seepage; and 3) piezometers installed in the embankment have shown an increase in pore pressure as a result of rises in the reservoir level.

1.2 Outline of the Thesis

The following topics will be discussed in this paper:

1.2.1 - Experimental Program (Chapter 2)

Laboratory tests were carried out in order to evaluate the properties and behaviour of a kaolinitic soil, in relation to internal erosion, during reservoir filling. The test results, and methods and materials used in the laboratory tests are presented in Chapter 2. It is also presented brief discussions related to the significance of each tests in the context of determining susceptibility to internal erosion. The author carried out the following tests:

a) Soil Mineralogy

- X-Ray Diffraction Analysis
- Determination of soil composition (noncrystalline clay materials, organic matter, and presence of salts)

b) Engineering Properties

- Atterberg Limits Using Cycles of Wetting and Drying, Intensive Remolding, and Variation of the Chemistry of the Pore-Water
- Determination of Clayeyiness Degree
- Shrinkage Factors of Soils by the Wax Method
- Determination of Volumetric Shrinkage of an Unsaturated Soil (Toluene Displacement Test)
- Classification of Expansive Soils by Sediment Volume Method
- Identification of Clay Type in Soils by the Free-Swell Technique
- Identification of Dispersive Clays
- Permeability Test Using Triaxial Cell

1.2.2 - Discussion of the Results (Chapter 3)

This chapter attempts to interpret the results of the lab tests obtained in this study and define the relationship among properties and behaviour of Na-kaolinitic soils in regard to internal erosion.

1.2.3 - Conclusions (Chapter 4)

The conclusions reached regarding the behaviour of one of the thin interbedded layers of low-permeability clayey silt soils. in relation to internal erosion, are the focus of Chapter 4.

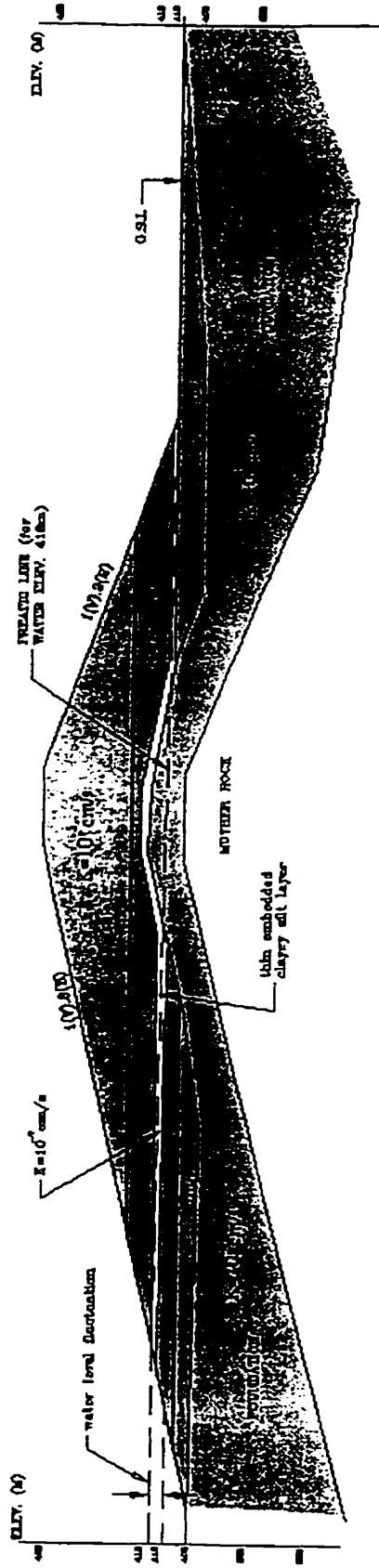


Fig. 1.1 - Cross Section of the hydraulic fill dyke studied

Chapter 2

Experimental Program

Laboratory tests such as Atterberg Limits, Dispersivity, Permeability, and Volumetric Changes were carried out to evaluate the properties and behaviour of a Na-kaolinitic soil during reservoir filling as related to internal erosion. Later, in Chapter 3 will be interpreted the results of the laboratory tests and defined their relationship in regard to internal erosion. The clayey silt soil used for the tests was taken from an interbedded thin layer which cuts the dyke's mass in an upstream-downstream direction (see Fig. 1.1). This chapter presents the materials and methods used for laboratory tests, and it is discussed the significance of each of the above tests in the context of determining susceptibility to internal erosion

2.1 Background Information

The dyke in this study was built by hydraulic fill method. This construction method used soils transported as slurry, that was pumped from a source of mature and young residual soils primarily composed of biotite-gneisses. In this dyke, the clay was deposited hydraulically which determined the in situ porosity and particle packing arrangement. The deposition of additional clay caused an increase in effective pressure and a decrease in water content; and at a certain stage, the clay was "normally consolidated" in the sense that it had not been subjected to a pressure greater than the present overburden.

2.2 Laboratory Tests

The tests were performed with remolded and intact specimens obtained from a shallow test pit excavation in the downstream slope of dyke 2 at an elevation of 419.09 m (MSL). This soil was classified as ferruginous clayey silt. It is usually reddish-brown in color, has a high plasticity index, is predominantly Na-kaolinitic with a clayeyness degree equal to 0.95 (Fig. 2.3).

2.2.1 - Soil Mineralogy

The mineralogy of this soil showed that Na-kaolinite is the dominant clay mineral. This soil is also composed of soluble chemical agents such as organic matter, aluminium and iron compounds; which under certain conditions could precipitate and form chemically stable cements which strengthen the links of the clay structure. The significance of mineralogy in the context of determining susceptibility to internal erosion will be interpreted in Chapter 3.

- X-Ray Diffraction Analysis

The mineralogical analysis of the soil was performed by way of a diffractometer and radiation. The dispersed clay fraction was solvated with glycerol, separated by sedimentation, saturated with magnesium, spread on a glass slide, and allowed to air dry. The X-ray diffraction pattern was recorded (Jackson, 1964). The untreated silt parts were also subjected to X-ray diffraction analysis.

The X-Ray Diffraction analysis identifies the type of clay mineral which associated to the salinity and pH of the pore-water is of fundamental importance in defining the soil fabric. The geometric arrangement of clay particles (clay fabric) indicates the soil susceptibility of internal erosion because the mechanism of internal erosion is due to deflocculation process where water travels through a leakage channel.

Deflocculation is a state of particle arrangement. The layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts. The results showed that Na-kaolinite is the dominant clay mineral. In Chapter 3 the type of clay mineral in conjunction with other factors will be interpreted in the context of determining susceptibility to internal erosion. The results of X-ray diffraction are shown in Figures 2.1 and 2.2.

- *Chemical Mineralogy*

Chemical tests were performed to identify the type and quantities of soluble chemical agents, in the soil studied. Noncrystalline clay material such as Al_2O_3 , Fe_2O_3 , MgO , and organic matter were found. The quantities of these soluble chemical agents are presented in Table 2.1. The presence of soluble chemical agents such as organic matter, and aluminium and iron compounds strengthen the links of the clay structure which makes the soil less susceptible to internal erosion. These chemical agents in conjunction with other factors will be interpreted in Chapter 3, in the context of susceptibility to internal erosion. These tests were performed based on the Ministry of Transportation, Ontario laboratory Testing Manual.

Table 2.1 shows some physico-chemical characteristics of the Na-kaolinite studied

Table 2.1 - Physico-chemical characteristics of the soil studied

Soil specimen	Location	Soil pH (average)	Chemical Mineralogy (%)			Insoluble residues	Organic matter	Clay and massive minerals (X-ray)
			F_2O_3	Al_2O_3	MgO			
1	Down-stream slope of Dike 2	5	8.3	7.2	0.7	70	13.8	Kaolinite, Quartz, and Mica

Data obtained by Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario - Foundation Lab.)

Note: The results represent an average of three specimens tested

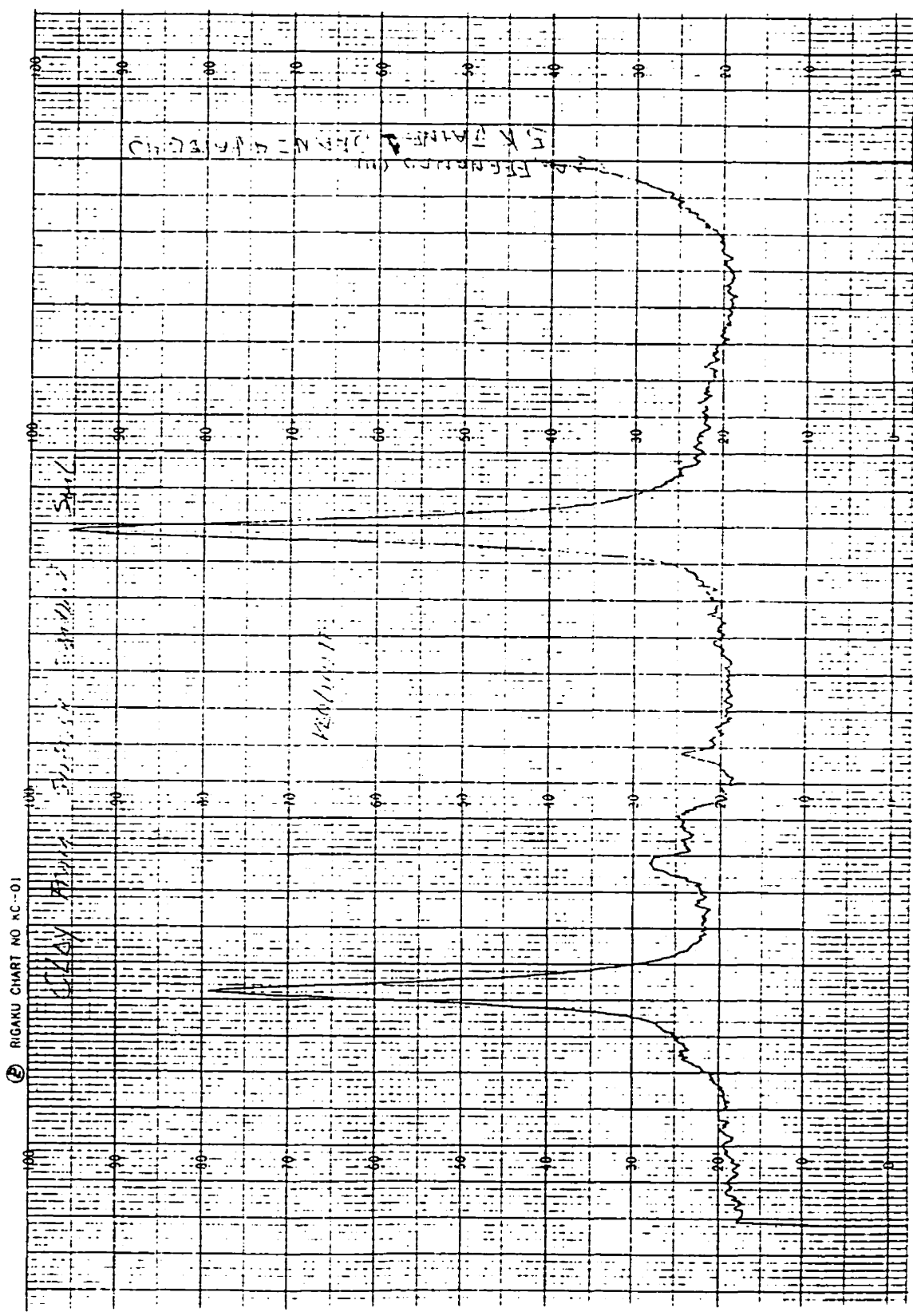


Fig. 2. 1 - X-Ray Diffraction of the Na-Kaolinitic Soil

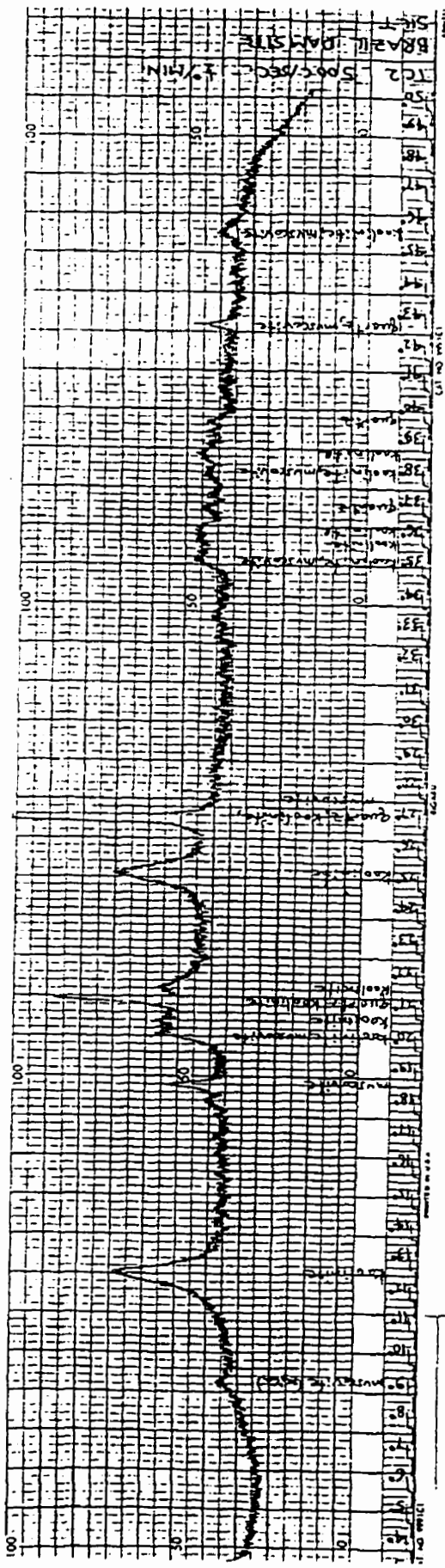


Fig. 2. 2 - X-Ray Diffraction of the Na-Kaolinitic Soil

2.2.2 - Engineering Properties

- *Atterberg Limits*

In the present study Atterberg limit values at two different salinities were used as an indicator of the in situ geometric arrangement of clay particles (clay fabric). The geometric arrangement of clay particles indicates the susceptibility of internal erosion if this arrangement is in a flocculated state and subjected to saturation by water with low total content of dissolved salts.

Atterberg limits were determined as per ASTM Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils (D 4318 - 93).

The Atterberg Limit tests that were performed by the author included cycles of wetting together with cycles of air and or oven drying (intensive remolding). The objective of these tests was also to evaluate the behaviour of the iron and aluminium oxides (cementing agents) under temperature variations and remolding cycles. As mentioned before these cementing agents strengthen the links of the clay structure (fabric) which makes the soil less susceptible to internal erosion.

The results obtained with Specimens = 1 and 2, as shown in Table 2.2, were reached by saturation of an intact sample in a triaxial cell, and placement of a portion of this specimen in the bowl of a Casagrande apparatus, using less disturbance of the soil paste. This was an attempt to obtain Atterberg limits at a natural state. These two specimens were called as quasi-remolded specimens.

Table 2.2 shows result of tests carried out on this Na-kaolinite at two different salinities. By saturating the soil with deionized water (fresh-water) of low pH the kaolinitic soil showed higher liquid limit and higher void ratio. By using salt-water (20 mg/L of NaHCO₃) with a high pH the kaolinitic soil showed a reduction in liquid

limit and void ratio. As expected, the Na-kaolinite with a relatively greater degree of particle flocculation enclosed larger void space for water entrapment and exhibited higher liquid limit values, while this kaolinite with a lesser degree of particle flocculation and with smaller void space possesses lower liquid limit values. Therefore, this is an indication of the in situ geometric particles arrangement (clay fabric). The results showed that the actual fabric is composed by Na-kaolinite in a flocculated particle arrangement.

Table 2.3 shows the results of some physical properties of the soil studied upon cycles of wetting, drying, intensive remolding, and variation of the chemistry of the pore-water.

Table 2.2 - Some Physical Properties of intact specimens at two different salinities and pH values

Soil Sample	Location	Sampling	Water for saturation (Type)	Particle size distribution			Specific gravity	Initial moisture content (%)	Initial Dry density (g/cm ³)	Quasi-remolded LL (%)	Quasi-remolded PL (%)	Quasi-remolded PI (%)	Soil Classif.	Initial void ratio	Void ratio at	Drying Process
				Sand (%)	Silt (%)	Clay (%)										
1	Down-stream slope of Dike 2	intact Sample	Deionized (pH= 6.83)	7	50	43	2.65	0.95	1.049	52	38	14	MH	1.526	1.39	air dried
2	Down-stream slope of Dike 2	intact Sample	2% NaHCO ₃ (20 g/l) (pH= 8.0)	7	50	43	2.65	0.95	1.049	44	33	11	ML	1.526	1.18	air dried

Data obtained by Fernando A. N. Silva - 1997 (Ministry of Transportation Ontario - Foundation Lab)

Table 2.3 - Some Physical Properties of Remolded Specimens Using Both Deionized and NaHCO₃ Pore-Water Including Drying and Wetting Cycles

Soil Sample #	Location	Water for saturation (Type)	Cycles of drying, wetting & remolding	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Soil Classif. (A. Casagrande)	Natural void ratio	Void ratio at LL	Drying Process
3	Down-stream slope of Dike 2	Deionized (pH= 6.83)	1st	51.5	39	12.5	MH	1.526	1.37	air dried air dried oven 110C air dried oven 60C oven 60C
			2nd	50.5	38	12.5	MH		1.32	
			3rd	48.5	37	11.5	MI		1.28	
			4th	51	39	12	MH		1.37	
			5th	51	37	14	MH		1.37	
			6th	51	36	15	MH		1.36	
4		Distilled (pH= 7.1)	1st	52	39	13	MH	1.526	1.39	air dried air dried oven 110C air dried oven 60C oven 60C
			2nd	50.5	38	12.5	MH		1.34	
			3rd	48.5	37	11.5	MI		1.3	
			4th	51.5	39	12.5	MH		1.36	
			5th	51	38	13	MH		1.36	
			6th	51	36	15	MH		1.35	
5		Deionized (pH= 7.46)	1st	50.5	38	12.5	MH	1.526	1.36	air dried oven 110C air dried oven 60C oven 60C
			2nd	48.5	37	11.5	MI		1.3	
			3rd	51.5	39	12.5	MH		1.37	
	4th		51	37	14	MH	1.36			
	5th		51	36	15	MH	1.35			
6	Spring water (HCO ₃ = 23.6mg/l) pH = 6.99	1st	51.5	39	12.5	MH	1.526	1.37	air dried oven 60C oven 60C	
		2nd	50.5	38	12.5	MH		1.35		
		3rd	51	38	13	MH		1.36		
		4th								
7	Spring water (HCO ₃ = 53mg/l) pH = 7.01	1st	51.5	39	12.5	MH	1.526	1.4	air dried oven 60C oven 60C	
		2nd	50.5	38	12.5	MH		1.34		
		3rd	51	38	13	MH		1.36		
		4th								
8	2% NaHCO ₃ pH = 8.34	1st	41.5	31	10.5	MI	1.526	1.11	air dried air dried oven 60C oven 60C	
		2nd	41	31	10	MI		1.1		
		3rd	40.5	30	10.5	MI		1.07		
		4th	40	29	11	MI		1.07		
9	4% NaHCO ₃ pH = 8.28	1st	42	31	11	MI	1.526	1.11	air dried	
10	5% (60 g / l) NaHCO ₃ pH = 8.02	1st	43	31	12	MI	1.526	1.14	air dried air dried oven 60C oven 60C	
		2nd	43.5	31	12.5	MI		1.16		
		3rd	42	29	13	MI		1.11		
		4th	41.5	28	13.5	MI		1.12		
11	deionized* pH = 6.4	none	51	34	17	MH	1.526	1.36	air dried	
12	deionized* pH = 6.72	none	51.5	35.5	16	MH	1.526	1.39	air dried	
13	deionized* pH = 6.97	none	51.5	37.5	14	MH	1.526	1.39	air dried	
14	KOH pH = 8.44	none	53	38	15	MH	1.526	1.42	air dried	
15	2mg/l NaHCO ₃ pH = 7.73	none	53.5	39	14.5	MH	1.526	1.42	air dried	

Data obtained by Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario - Foundation Lab.)

Note: deionized* = deionized water + dissolved CO₂ (amount represented by means of acidity)

- *Shrinkage factors*

The shrinkage factors of the soil studied were determined by ASTM Test Method for Shrinkage Factors for Soils by the Wax Method (D 4943 - 89). Two different conditions of chemistry of the pore-water were used, as shown in Table 2.4. The shrinkage limit in conjunction with liquid limit are indicators of the geometric arrangement of clay particles (fabric). In other words, a kaolinitic soil with a greater degree of particle flocculation and a higher liquid limit would shrink less. Therefore, the shrinkage limit confirmed that the in situ fabric is in a flocculated arrangement, which indicates susceptibility to deflocculation when saturated by water with low total contents of dissolved salts.

Table 2.4 - Shrinkage Factors of the soil studied according to the Wax Method

Soil Sample	Location	Sampling	Water for saturation (Type)	Shrinkage limit (%)	Shrinkage ratio	Linear shrinkage (%)
16	Down-stream slope of Dike 2	Remolded sample	deionized pH=6.83	16.3	1.71	16.31
17			2% (20 g / l) NaHCO ₃ pH= 8.02	18.62	1.64	13.11

Data obtained by Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario-Foundation Laboratory.)

Note: The results are averages of tests performed on three specimens

- *Volumetric changes during air drying*

In order to evaluate the dispersion potential upon water immersion the Toluene test was performed. This test indicated that the soil in study will be subjected to dispersion upon water immersion (re-wetting), which leads to susceptibility to deflocculation and internal erosion. This behaviour is interpreted later in Chapter 3.

The volumetric change of the soil in question while drying was determined by the fluid displacement method (Sibley, J. W. and Willians, D. J., 1989). The purpose of this method is to measure the volume of a fluid displaced by the specimen upon drying and the changes in the total volume of the soil (water + solids + air). Toluene was used as the displacement fluid because it is lighter than water, immiscible in with water, evaporates quickly, and is unreactive to soil.

Table 2.6 shows the results of the volumetric changes of the soil studied during air drying.

- *Determination of Clayeyess Degree*

The clayeyess degree was obtained in order to confirm the type of dominant clay mineral of the soil studied.

Recently studies performed mostly on tropical residual soils have attempted to classify residual soils as a whole, taking into account the nature of the clay-fraction and the relative influence of this fraction on the fines fraction, and vice versa, and the nature of the fines grains. Soria (Doctoral Thesis, 1985) suggested a numerical representation of this approach by using a factor which he called "Clayeyess Degree." Soria used the liquid limit index to identify the clay fraction itself in numerical and relative terms. Soria's clayeyess degree diminishes the margin of error found in some existing methods which utilize Skempton's colloidal activity and plasticity index to classify residual soils. Clayeyess degree can be defined as follows:

(Equation 2.1)

C.D. = f[LL; LL'; (% of fines grains < 0.42mm); (% of clay < 2mm)]

$$C.D = [(LL/100) \times (LL'/100)] + [(LL/100) \times (\% < 0.42\text{mm}) / 100] + [(LL'/100) \times (\% < 2\text{mm}) / 100]$$

The product LL x LL' reflects the influence of the nature of the clayey fraction on the fines fraction and consequently the relative influence of each fraction. The product LL multiplied by the percentage of the fines fraction indicates the relative influence of the fines fraction on the soil as a whole; and the product LL' multiplied by the percentage of the clayey fraction reflects the influence of the clayeyness on the soil taken as a whole. The Na-kaolinite mineral was ascertained from relationships of plasticity index with clayeyness degree and cation exchange capacity values.

Table 2.5 shows the result of the clayeyness degree of the soil studied.

Table 2.5 - Determination of Clayeyness Degree

Soil Sample	Location	Sampling	Water for saturation (Type)	Fine Fraction		Clay Fraction		Clayey-ness Degree (C.D.)
				% < 0.425 m	LL (%)	% < 10 μm	LL' (%)	
18	Down-stream slope of Dike 2	Dry Sample	Deionize (pH= 6.83)	98	52	30.2	55	0.95

Data from Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario-Foundation Lab.)

The author developed associated plasticity and mineralogy charts which include the clayeyness degree and cation exchange capacity. Both the charts (Fig. 2.3) were used to classify the residual Na-kaolinitic soil studied.

Table 2.6 - Volumetric Changes in kaolinitic Residual Soils upon Air Drying

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Date/Time	(Soil + Stopper + Flask) MTF (g)	(MTF - MDSolids) Water Mass Mw (g)	(Mw/Mds) x 100 Water content w (%)	Water temp Tw (°C)	Water density ρw g cm ⁻³	(Mw/ρw) = Water volume Vw cm ³	(Soil + stopper + Flask + Toluene) MSTFT (g)	(MSTFT - MTF) = Toluene mass MTOL (g)	Toluene temp TTOL (°C)	Toluene density ρTol (g cm ⁻³)	(MTOL / ρTol) Toluene volume VTOL (cm ³)	(VF - VTOL) = Soil volume VT (cm ³)	VT-Vw-VS = Air volume VA (cm ³)	(VA/VT) x 100 = Air content A (%)
25/01/97	44.897	0	0	22	0.9915	0	83.066	38.169	22.5	0.947	40.30517	9.694826	4.815226	49.668
25/01/97	44.897	0	0	22	0.9915	0	60.6495	15.7525	22.5	0.947	16.63411	33.36589	28.48629	85.37548
27/01/97	44.897	0	0	22	0.9915	0	55.0319	10.1349	22.5	0.947	10.70211	39.29789	34.41829	87.58305
04/03/97	44.897	0	0	22	0.9915	0	53.8138	8.9168	22.5	0.947	9.415839	40.58416	35.70456	87.97659
05/03/97	44.897	0	0	22	0.9915	0	53.5428	8.6458	22.5	0.947	9.129673	40.87033	35.99073	88.06078
10/03/97	44.897	0	0	22	0.9915	0	52.4293	7.5323	22.5	0.947	7.953854	42.04615	37.16655	88.39466
11/03/97	44.897	0	0	22	0.9915	0	52.1291	7.2321	22.5	0.947	7.636853	42.36315	37.48355	88.4815
12/03/97	44.897	0	0	22	0.9915	0	51.8816	6.9846	22.5	0.947	7.375502	42.6245	37.7449	88.55212
14/03/97	44.897	0	0	22	0.9915	0	51.4554	6.5584	22.5	0.947	6.925449	43.07455	38.19495	88.67173
18/03/97	44.897	0	0	22	0.9915	0	50.5296	5.6326	22.5	0.947	5.947835	44.05216	39.17256	88.92313
20/03/97	44.897	0	0	22	0.9915	0	50.0134	5.1164	22.5	0.947	5.402746	44.59725	39.71765	89.05852
25/03/97	44.897	0	0	22	0.9915	0	48.8051	3.9081	22.5	0.947	4.126822	45.87318	40.99358	89.36285
01/04/97	44.897	0	0	22	0.9915	0	47.1688	2.2718	22.5	0.947	2.398944	47.60106	42.72146	89.74897
02/04/97	44.897	0	0	22	0.9915	0	46.9152	2.0182	22.5	0.947	2.131151	47.86885	42.98925	89.80631
03/04/97	44.897	0	0	22	0.9915	0	46.6801	1.7831	22.5	0.947	1.882893	48.11711	43.23751	89.85891
07/04/97	44.897	0	0	22	0.9915	0	45.8836	0.9866	22.5	0.947	1.041816	48.95818	44.07858	90.03313
08/04/97	44.897	0	0	22	0.9915	0	45.6173	0.7203	22.5	0.947	0.760612	49.23939	44.35979	90.09005
09/04/97	44.897	0	0	22	0.9915	0	45.3907	0.4937	22.5	0.947	0.521331	49.47867	44.59907	90.13757
11/04/97	44.897	0	0	22	0.9915	0	45.0629	0.1659	22.5	0.947	0.175185	49.82482	44.94522	90.20649
16/04/97	44.897	0	0	22	0.9915	0	44.7825	-0.1145	22.5	0.947	-0.12091	50.12091	45.24131	90.26434
18/04/97	44.897	0	0	22	0.9915	0	44.7652	-0.1318	22.5	0.947	-0.13918	50.13918	45.25958	90.26789
21/04/97	44.897	0	0	22	0.9915	0	44.7608	-0.1362	22.5	0.947	-0.14382	50.14382	45.26422	90.26879
22/04/97	44.897	0	0	22	0.9915	0	44.7608	-0.1362	22.5	0.947	-0.14382	50.14382	45.26422	90.26879

Data from Fernando A N Silva - 1997 (Ministry of Transportation Ontario-Foundation Laboratory)

Sample Preparation.

Stopper Mass = 4.179 g
 Flask-Stopper = 31.966 g
 Flask Mass (MF) = 27.786 g
 Flask Volume (VF) = 50 cm³
 Flask + Toluene = 75.144 g
 Toluene Mass (MTOL) = 47.358 g
 Toluene Density r TOL = 0.947 g cm⁻³
 Toluene Temperature TTOL = 22.5 °C

Sample Solids Volume VDS (Complete after drying):

Flask + air and oven (105 °C) dried solids (MFDS) = 44.897 g
 Mass of Solids (MDS) = 12.931 g
 Water Density rw = 0.9915 g cm⁻³ (Temp 22 °C)
 Flask Type = 50 ml
 Solids Spec. Gravity (GS) = 2.65
 Volume of Solids VS = 4.8796 cm³
 Sample Temperature = 22 °C

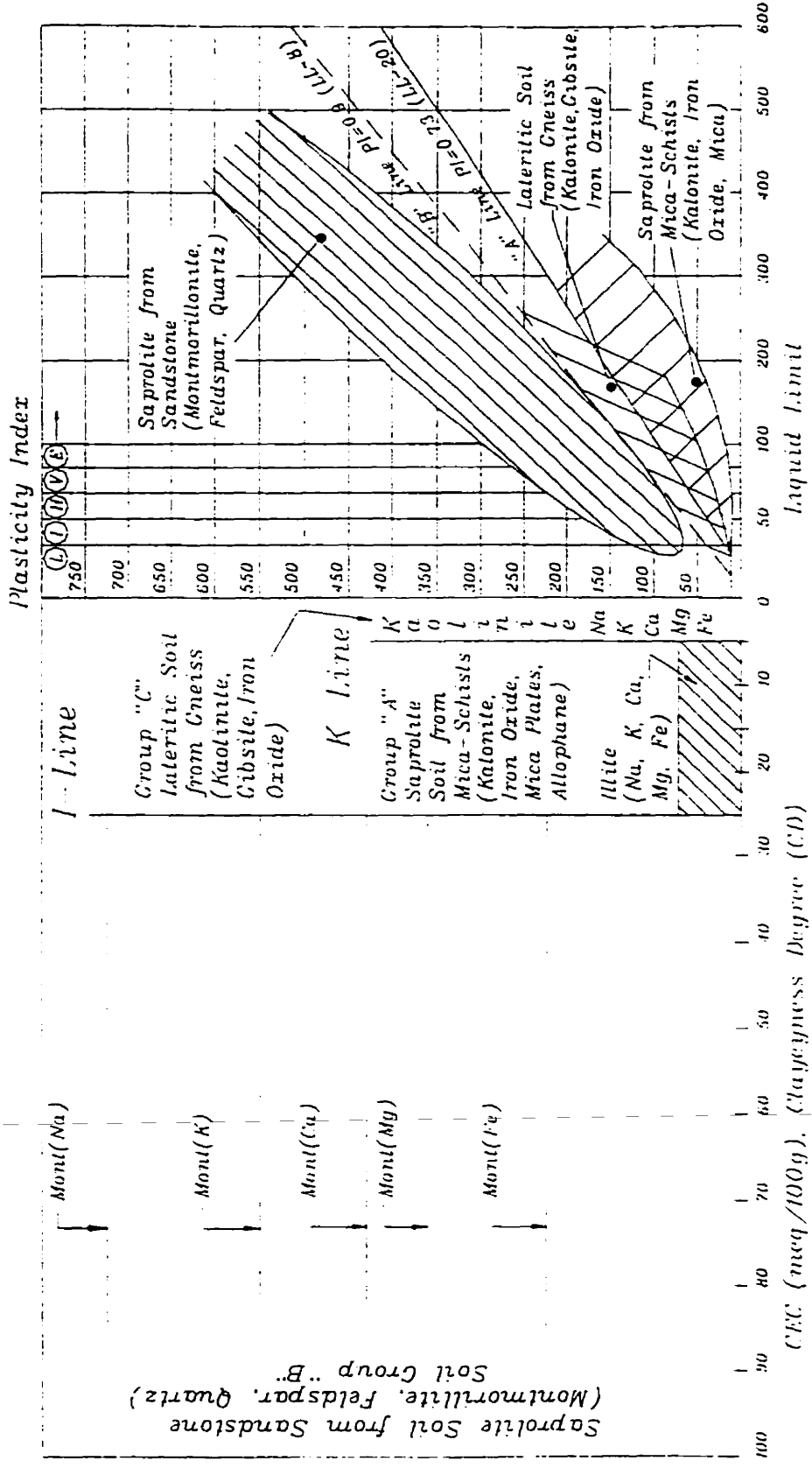


Fig. 2.3 - Plasticity and Mineralogy Charts

- *Classification of Expansive Soils by Sediment Volume Method and Free-Swell Technique*

The sediment volume tests were performed in order to evaluate crack potential and to obtain an indication of the in situ soil particles arrangement. The results were interpreted in the context of determining susceptibility to internal erosion. Cracks are a precursor to erosion and must be prevalent for erosion to initiate. The sediment volume in conjunction with liquid limit and/or shrinkage limit are indicators of the geometric arrangement of clay particles (fabric). In other words, a kaolinitic soil with a greater degree of particle flocculation and a higher liquid limit should shrink less and/or occupy a higher sediment volume. Therefore, the sediment volume confirmed that the in situ fabric is in a flocculated arrangement, which indicates susceptibility to deflocculation when saturated by water with low total contents of dissolved salts.

Identification of the presence of nonswelling clay, swelling clay, or a mixture of the two types of clays in the soil specimens was determined by the sediment volumes occupied by 10 g of dry soil in 100 ml of distilled water and carbon tetrachloride, respectively, under no external constraint. The tests were performed by pouring 10 g of dry soil specimen into a 100 ml graduated cylinder containing about 40 ml of distilled water and carbon tetrachloride, respectively. The suspensions were stirred repeatedly and allowed to equilibrate for 24 hours to ensure thorough wetting of the soil specimen and then the cylinder was filled to the 100 ml mark with more distilled water and carbon tetrachloride, respectively. The graduated cylinders were stoppered and left undisturbed for periods ranging from 24 to 288 hours, at which times the volume occupied by soil particles on settling (the sediment volume) were recorded and expressed as cm^3 / g .

The free-swell index of the soil was calculated as:

$$\text{free-swell index} = (V_d / 10)$$

where V_d is the free-swell volume of 10 g of the dry soil specimen read from the graduated cylinder. The procedure was repeated for the soil in nonpolar carbon tetrachloride.

The sediment volume tests were performed on Na-kaolinitic soil at two different salinities. Table 2.7 shows the results of sediment volume tests.

Table 2.7 - Sediment Volume Method and Free-Swell Technique

Test Type	Location	Soil Sample	Sampling	Time (hours)				
				6 h	24 h	48 h	72 h	288 h
				Sediment Volume (cm ³ /g)				
Sediment Volume in Distill. Water (cm ³ /g)	Down-stream slope of Dike 2	19	Dry fresh-water kaolinite	1.89	1.9	1.9	1.9	1.9
		20	Dry salt-water kaolinite (with 2 % NaHCO ₃)	1.25	1.27	1.27	1.27	1.27
Sediment Volume in Carbon Tetrachl. (cm ³ /g)		21	Dry fresh-water kaolinite	2.35	2.35	2.35	2.35	2.35

Data from Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario-Foundation Lab.)

Table 2.8 - Expansivity Classification

Sedim. Volume-water (cm ³ /g)	Sedim. Volume-Carbon Tetrachl. (cm ³ /g)	Clay type	Soil Expansivity
> 1.50	1.1 to 3.0	Non-swell	Negligible
1.5 to 2.0	< 1.1 and < sed. vol in water	Mixture swell. & nonswell.	Low
1.5 to 2.0	≤ 1.10		Moderate
2.0 to 4.0	≤ 1.10		High
> 4.0	≤ 1.10		Very high

(After Sridharan et al., 1990)

- *Identification of Dispersive Clays*

The following tests were performed because the identification of soil dispersiveness is of fundamental importance in determining internal erosion. With dispersive clay, internal erosion is due to a deflocculation process where water travels through a leakage channel, such as a crack.

Two tests were performed for identification of dispersive clays such as the SCS (Soil Conservation Service) laboratory dispersion or double hydrometer test, and the TDS (Total Dissolved Salts) method. This test was developed and has been widely used since 1940 by the U.S. Soil Conservation Service. It involves the measurements of particle size distribution by two hydrometer tests: one with and one without a chemical dispersant. By definition, the percent dispersion is the ratio of the size of the particles (< 0.005 mm) in the two tests (Sherard et al., 1977).

For the SCS test, the particle-size distribution was first determined by the standard hydrometer test in which the soil specimen is dispersed in distilled water with strong mechanical agitation and a chemical dispersant. A parallel hydrometer test was then performed on a duplicate soil specimen, but without mechanical agitation and without a chemical dispersant. By definition, the "percent dispersion" is the ratio of 0.005 mm diameter particles of the second test to the first, expressed as percentage.

The Table

2.9 shows the results of the SCS Double Hydrometer Test.

Table 2.9 - SCS Double Hydrometer Test

Soil Sample	Location	Sampling	Particle-Size Analysis % < 0.005 mm		
			Without Mech. Agitation and Disp. (A)	Mech. Agitation Disp. (B)	Percent Disp. (A/B)x10
22	Down-stream slope of Dike 2	Dry Sample	1	43	2.3

Data obtained by Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario - Foundation Laboratory)

The TDS method carried out displaced the exchangeable calcium, magnesium, sodium and potassium cations. The method used about 40 g of soil centrifuged at 6000 rpm. From this amount, 2.5 g of pore-water was extracted. The specimens were diluted 20 times and analysed for Ca and Mg by atomic absorption spectrometry and for Na and K by flame atomic emission spectrometry. To obtain the saturation extract, the soil was mixed with distilled water until a saturated soil paste with moisture content near the Atterberg liquid limit was obtained. The paste was allowed to repose inside a container for 24 hours until equilibrium had been attained

between the salts in the pore water and on the cation exchange complex. Subsequently, a small quantity of pore-water was filtered from the soil paste with a vacuum. This extracted pore-water was tested by way of a routine chemical test, to determine the amount of the main metallic cations (calcium, magnesium sodium, and potassium) in terms of mliequivalents per litre as described above,. The percent of sodium and total dissolved salts was computed from the sum of the main metallic cations.

The SAR (sodium absorption ratio) is a parameter that commonly quantifies the role of sodium with respect to dispersion when free salts are present in the pore water:

$$SAR = \frac{Na}{\sqrt{0.5(Ca + Mg)}}$$

Note: Unit in meq /L

Table 2.10 shows the results of the TDS tests. The potential dispersiveness of this Na-kaolinitic soil is shown in Figures 2.3 and 2.4.

Table 2.10 - Total Dissolved Salts

Soil Sample	Water of saturation of the sample at LL		Total Dissolved Salts (TDS) (meq / l)					
	Type	pH	Ca ^{**}	Mg ^{**}	Na ^{**}	K ^{**}	TDS	(%) of Na
3	deionized	6.83	0.0717	0.0717	0.679	0.333	1.1554	58.77

Data from Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario - Foundation Lab.)

Notes:

(1) - ** Pore water extracted by centrifugal force. Calcium and Magnesium analysed by flame atomic absorption spectrometry using Perkin-Elmer 5000 AA spectrometer. Sodium and Potassium determined by atomic emission spectrometry on Pye-Unicam 900 spectrometer. Carbonates were established as alkalinity by titration.

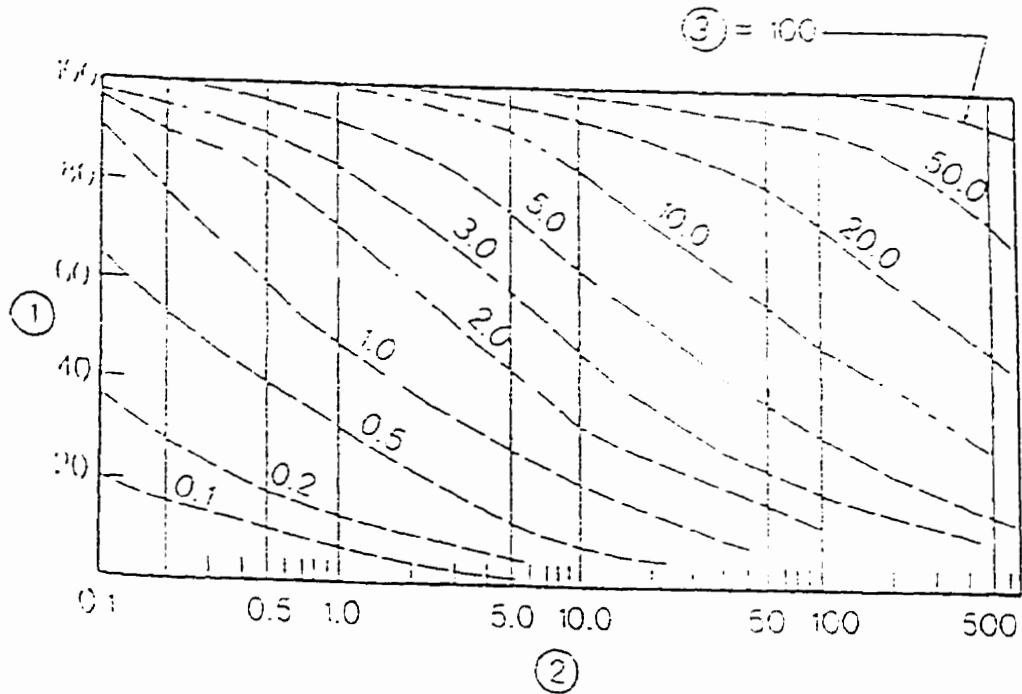


Figure 2.4

Potential dispersiveness chart (SAR)

(After Sherard, et al.)

(1) Percent sodium

$$= \frac{Na(100)}{TDS(\text{TotalDissolvedSalts})}$$

(2) Total dissolved salts in saturation extract

$$TDS = Na + Ca + Mg + K \text{ (meq /L).}$$

$$(3) SAR = \frac{Na}{\sqrt{0.5(Ca + Mg)}}$$

Note: All units in meq /L of saturation extract.

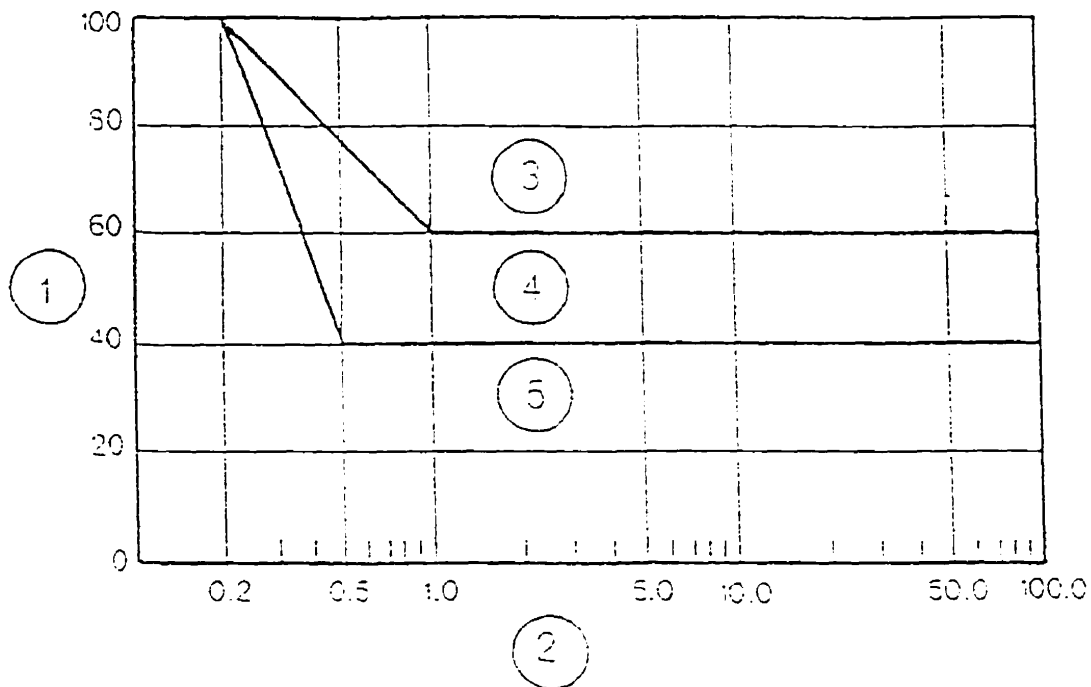


Figure 2.5
Potential dispersiveness chart
(After Sherard, et al.,)

(1) Percent sodium in saturation extract

$$= \frac{Na(100)}{TDS}$$

(2) Total dissolved salts in saturation extract

$$TDS = Na + Ca + Mg + K$$

Note: Unit in meq. /L

(3) Dispersive behaviour zone.

(4) Intermediate behaviour zone.

(5) Non-dispersive behaviour zone.

- *Permeability test using triaxial cell*

Laboratory permeability tests were performed with intact specimens from a hydraulic fill (dike 2). Two different pore-water salinities were used to evaluate changes in soil fabric. Table 2.11 shows the results of permeability of the soil studied. Permeability tests at two different salinities of pore-water indicate the condition of the in situ soil fabric and its susceptibility of internal erosion. The influence of clay fabric on internal erosion was ascertained from relationships of Atterberg limits, dispersivity, permeability, sediment volume, and volumetric changes of this Na-kaolinitic soil. In the view of susceptibility to internal erosion, the results of permeability are interpreted in Chapter 3.

The permeability tests were carried out with triaxial cells. The triaxial test apparatus is able to maintain a water flow through a sample under a known difference of pressure and measure the rate of flow while the sample is being subjected to a known effective stress. The advantages of measuring permeability in a triaxial cell are:

- Saturation of the sample under application of a back pressure, and reducing or eliminating obstructions to flow due to bubbles of gas.
- The test can be carried out under effective stresses and at pore pressures which simulate field conditions.
- Small rates of flow can be measured easily.
- A wide range of hydraulic gradients can be applied and accurately measured.
- Undisturbed test samples can be set up easily, and there are no cell wall effects which might give non-uniform flow conditions.

A constant head procedure was used to measure permeability. In the present tests, water was made to flow through cylindrical specimens under the application of a

pressure difference which remained constant, i.e. under a constant head. The amount of water (measurements of the influent and effluent volumes) passing through the soil at a given time was measured, and the permeability of the specimen was calculated by using equation $K = Q/(Ai)$, where:

- Q is the quantity of water (cm³) at T°C passes through the sample at "t" (sec.) at steady influent and effluent flows;
- hydraulic gradient "i" is equal to $(h_1 - h_2) / L$, where $(h_1 - h_2)$ is equal to the head loss along the length of sample "L";
- "L" is the length of the sample; and
- "A" is the area of cross-section of the sample.

De-aired water was used to avoid bubbles of air in the voids between soil particles. Two types of water were used for the tests, such as de-ionized water and water with 20 g /L of NaHCO₃. A filter made of "concrete sand" was used in the outlet flow side of the specimen to retain transported fine grains from the sample. A grain-size analysis in the filter material was performed before and after the test to investigate contamination with the transported fine grains.

Table 2.11 - Permeability test on thin interbedded kaolinitic layer

Soil Sample #	Fluid type	Location	Sampling	Conf. pressure σ_3 (Kpa)	Const. head H (Kpa)	Gradient i	Coef. of Permeab K (cm/sec)
23	(20 g /L) NaCHO ₃ pH=8.02	Dike 2	Intact Dry Sample	30	20	5	6.4×10^{-6}
29	Deion.W			30	10	5	1.7×10^{-7}
30	pH=6.83			30	20	5	2.6×10^{-7}
31				30	30	5	2.8×10^{-6}

Data obtained by Fernando A.N. Silva - 1997 (Ministry of Transportation Ontario-Foundation Laboratory.)

- *Chemical and physical characteristics of the Lajes reservoir's water*

Table 2.12 shows the seasonal data obtained from the Lajes reservoir's water before and after seepage through the foundation of the dikes studied. These tests were performed because one of the properties governing the susceptibility of internal erosion of this Na-kaolinitic soil is the total content of dissolved salts in the reservoir water: the lower the dissolved salts, the greater the susceptibility of internal erosion of the soil studied.

Table 2.12 - Physico-chemical Characteristics of the Lajes Reservoir's Water Before and After Seepage Through the Foundation of the Dikes

Chemic. Test (mg /L)	Before Seepage Through Foundation					After Seepage Through Foundation				
	Summer		Winter		Summer	Summer		Winter		Summer
	Nov-91	Feb-92	Jun-92	Jul-92	Jan-93	Nov-91	Feb-92	Jun-92	Jul-92	Jan-93
CO2	0.55	1	1	1	1	0.55	2	3	2	1.5
Alkalinity (HCO ₃)	8.1	10.2	13.46	13.4	20.33	65.1	107.8	137.24	143	136.23
Alkalinity (CaCO ₃)	3.9	5.3		4.7	0.33	11.9	11.2		12.2	2.23
Hardness	12	24	38	30	32	64	96	99	142	109
Ca (CaCO ₃)	2.4	6	14	10	11.6	9.6	31.6	26.8	31.2	15.2
SiO ₂	7	16	8	6.5	10	20	40	25	8	20
Fe	0.1	0.9	0.05	0.6	0.25	0.3	1.1	0.1	1.2	0.1
pH	6.81	6.15	6.7	6.39	6.4	6.81	7.14	7.25	7.5	7
Conductivity (s)		29.3		35			252		560	
Chloride			2	2.5				2.5	3	
SO ₄	6.7			10.7	8.64	14			7.8	32.92
MgCO ₃					20.4					93.8
Na					2					10.3
K					0.8					8.8

Data obtained by Fernando A.N. Silva - Nov/91 to Jan/93 (Light S.E.S.A. Chemical Laboratory.)

Chapter 3

Discussion of the Results

This chapter will interpret and establish interrelationships among the results obtained in Chapter 2. The discussion of the results will be derived from the internal erosion point of view. The dominant clay mineral of the soil in study is Na-kaolinite, which is a residual clay formed from the alteration of the gneiss; and it ranges from dispersive to non-dispersive. Laboratory tests have shown that the in situ soil fabric is characterized by an assemblage of positive edge-negative face flocculation. The main concern is in regard to internal erosion during reservoir filling, because the layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts. With dispersive clay, internal erosion is due to deflocculation process where water travels through a leakage channel, such as a crack, and the erosion of the wall of the leakage channel occurs simultaneously along its entire length. Furthermore, the Toluene Displacement tests showed that upon water immersion this soil may lead to dispersion, which increases its susceptibility of deflocculation and internal erosion. This soil has no tendency for self-healing as shown by sediment volume tests, which makes the soil more vulnerable to internal erosion.

3.1 Atterberg limits

In the present study the Atterberg Limits were used as an indicator of the in situ geometric arrangement of clay particles (fabric). The geometric arrangement indicates the susceptibility of internal erosion if this arrangement is in a flocculated state and subjected to saturation by water with low total content of dissolved salts.

3.1.1 *Relationship between Atterberg limits and Fabric*

Yong and Warkentin (1966) have shown that interparticle forces play a prominent role in determining the liquid limit of kaolinitic clays. Interparticle forces determine the particle arrangement (fabric), which, in turn, regulates the liquid limit values. Saturation of kaolinite with mono-valent sodium ions results in weak interparticle repulsion, and less degree of flocculation. The interrelationships mentioned above mean that varying the salinity of the pore-water will affect the net interparticle forces, the geometric particle arrangement, and liquid limit.

In view of the results from Tables 2.1 to 2.3, it is likely that the geometric arrangement of clay particles (clay fabric) regulates the liquid limit of kaolinitic soils. Soils with a relatively greater degree of particle flocculation enclose larger void spaces for water entrapment and exhibit higher liquid limit values; while soils with a lesser degree of particle flocculation and smaller void spaces possess lower liquid limit values and are less susceptible to internal erosion. [See results of samples 3 and 8 (Table 2.3)].

3.1.2 - *Relationship between Atterberg limits and Sediment volume*

The liquid limit may also be related to the sedimentation volume of the soil in water as is shown in Table 2.7. Generally speaking, the larger the sediment volume after sedimentation, the higher the degree of flocculation (Lambe, 1958). Sediment volumes of flocculated suspensions are usually large because the strong attractive forces between settling particles facilitates particle aggregation, thus leading to a high sediment volume. If there is a barrier to flocculation owing to weak interparticle repulsion, the sediment volume decreases since the particles have become much more mobile and thus pack more tightly (Van Olphen, 1963), making this type of soil less susceptible to internal erosion. As shown in Table 2.7, kaolinitic soil with a higher liquid limit possesses a stronger interparticle repulsion and a greater degree of particle flocculation. Consequently, it is expected to occupy a

higher sediment volume in water. An increase in the liquid limit is accompanied by an increase in sediment volume, which is a confirmation of the theory that the liquid limit of this kaolinitic soil is a function of the clay fabric.

3.2 - Pore-water pH

When soil acidity increases, there is a concomitant increase in the numbers of H^+ ions available for interaction with edge hydroxyl groups accompanied by a higher edge positive charge and a higher degree of flocculation (Schofield and Samson, 1954).

Likewise, Bjerrum (1954) concluded that the disintegration of feldspar, mica, and chlorite will commence if pore-water pH is reduced to a sufficiently low value. The disintegration results in the liberation of cations of a high order which subsequently collect on the surface of the clay particles. The effect of this base-exchange increases clay plasticity and makes soil less susceptible to internal erosion. See results of samples 5 (pH = 7.46) and 11 (pH = 6.4) from Table 2.3. The disintegration also causes the liberation of other chemical compounds, which tends to increase the pH level, thereby thwarting the strengthening process. For example, to make the soil less susceptible to internal erosion via exchange of Na^+ ions for ions of a higher order it would require that pH-reducing agents be continuously supplied to the clay.

3.3 - Cementing agents

Another condition which may lead to the development of additional soil strength is the precipitation of cementing agents. For the most part, the effect of such a precipitation is limited to a strengthening of the links of the clay structure while the clay itself remains unaffected. Table 2.1 shows some existing soluble chemical agents in the soil, such as organic matter, aluminium, and iron compounds, which, under certain conditions, can precipitate and form chemically stable cements that are of considerable strength. The cementing agents develop bonded structures due to the physical connections between particles which makes this kaolinitic soil less

susceptible to internal erosion. A bonded structure can be destroyed by remolding and de-structuring, which results in a decrease in plasticity. However, intensive cycles of remolding can re-form the bonded structure quite rapidly, thereby causing an increase in plasticity (Table 2.3). Hydrated oxides of iron and aluminium may become less plastic (lower Atterberg limit values) after drying. This is because dehydration of the sesquioxides creates a stronger bond between particles, which then blocks water penetration and which cannot be reversed by re-wetting. This behaviour is more pronounced upon oven-drying at high temperatures (see results of samples 3, 4 and 5 from Table 2.3).

3.4 Shrinkage limit

When the water content of a fine-grained soil is reduced to below the plastic limit, shrinkage of the soil mass continues until the shrinkage limit has been reached. At that point, the solid particles are in close contact with each other and the water contained in the soil is sufficient to fill the voids. Further reduction of water content cannot bring the particles closer together, so there is no further decrease in the volume of the soil mass. Below the shrinkage limit, the soil is considered to be a solid, in which case the particles remain in close contact. The *shrinkage limit* represents the exact amount of water required to fill all the voids of a given cohesive soil at its minimum void ratio obtained by oven-drying. The shrinkage limit can be used to evaluate the soil shrinkage, crack development, and swell potential of earthwork involving cohesive soils. Internal erosion is related to deflocculation process and concentrated leak through a crack. Therefore, kaolinitic soils with greater degree of particle flocculation and lesser shrinkage are susceptible to internal erosion.

3.4.1 - Interrelationships among shrinkage limit, liquid limit, and fabric in the context of internal erosion

Table 2.4 shows that when the kaolinitic soil in study is saturated with a saline pore-water (20 g of NaCHO₃/ L) possesses a larger shrinkage limit than a fresh-water

kaolinitic soil (deionized water). Lambe (1958) observed that, upon drying, the amount of shrinkage can be used as a measure of an average particle orientation.

In addition, soils with lesser degree of particle flocculation should undergo more volume reduction upon drying than the same soil whose particles are in a random-flocculated arrangement (fabric). Lambe then concluded that the more nearly parallel the particles were, the greater the shrinkage of the soil would be upon drying. Therefore, a kaolinitic soil with a greater degree of particle flocculation and a higher liquid limit (see Table 2.2) should undergo lesser shrinkage than the same kaolinitic soil with a lesser extent of particle flocculation and a lower liquid limit. The results of Table 2.4 show that the actual field conditions, has high degree of particle flocculation and shrinks less. In addition, these results show that this Na-kaolinitic soil is susceptible to internal erosion.

3.5 Volumetric changes during air drying

The Toluene Displacement Tests showed that upon water immersion this soil may lead to dispersion, which increases its susceptibility of deloculation and internal erosion.

When a mass of saturated soil is exposed to the atmosphere, and evaporation of water is allowed to take place, a decrease in volume occurs until the air-entry pressure has been reached (equilibrium). Upon reaching equilibrium, soils that behave similar to elastic materials increase in volume until they have attained the same volume when saturated, while plastic soils increase very little in volume.

The toluene test results seen in Table 2.6 show that the soil under study behaved in the same way as elastic materials. The volume decrease continued until the air-entry pressure had been reached, at which point the volume started to increase. Furthermore, when the soil had completely dried and pore-water pressure was equal to zero ($u = 0$), the soil attained the same volume as when it was saturated (see

Kenney, 1997). The toluene test results also showed that the swelling induced a reduction in the soil effective stress, which, when combined with the developed air pressure in the soil voids, may cause the breakdown of soil aggregates and eventually lead to dispersion on immersion in water (re-wetting).

3.6 - Determination of clayeyness degree

The clayeyness degree was obtained in order to confirm the type of the dominant clay mineral in the soil studied.

When attempting to determine the clayeyness degree of a soil, an important consideration to keep in mind is that under normal lab conditions, it is not feasible to successfully carry out the liquid limit test on clayey fractions of less than $2\mu\text{m}$. In this connection, Soria (1985) has suggested that the best separation point is 0.01 mm ($10\mu\text{m}$). So, for practical reasons, the percentage $< 2\mu\text{m}$ of the equation (Eq. 2.1), could be replaced by the percentage $< 10\mu\text{m}$. Tests were performed according to Soria's recommendations and the value of clayeyness degree of the soil studied was $CD = 0.95$; while the liquid limit was $LL = 52\%$; and the plasticity index was $PI = 14$. This soil had a cation exchange capacity of $CEC \cong 5\text{ meq}/100\text{g}$; and classified as kaolinitic residual soil according to the author's combined plasticity and mineralogy charts (Fig. 2.3).

3.7 - Classification of expansive soils according to sediment volume

Sediment volume tests were performed in order to evaluate crack potential and obtain an indication of the in situ soil particles arrangement. The results were interpreted in the context of determining susceptibility to internal erosion of the soil studied.

Identification of expansive soils based on the sediment volume procedure is the most reliable method for estimating soil expansion in relation to index properties (Sridharan, A., Rao, S. M. and Joshi, S., 1990).

It is well known that the presence of dissolved electrolytes in pore water minimizes interparticle repulsion and accelerates the settling process. In the present research, the influence of dissolved pore electrolyte concentration on the settling time of a kaolinitic soil was studied. The laboratory tests showed that this kaolinitic soil rapidly settles, i.e., it takes between 24 and 48 hours to attain sediment volume equilibrium in water. Table 2.7 presents the time period this soil requires to attain sediment volume equilibrium in fresh-water, salt-water (20 g NaHCO₃/ L), and in carbon tetrachloride solutions. The results showed that the presence of dissolved sodium in the pore water (20 g NaHCO₃/ L) does not lead to a significant decrease in the time period required to attain sediment volume equilibrium. It was also observed that the dissolved 20 g NaHCO₃/ L caused a decrease in sediment volume when compared with the results obtained from fresh-water solutions. These results indicated that for the kaolinitic soil studied, the increase in pore electrolyte concentration led to a suppression of the diffuse ionic layer thickness and, consequently to, a lower sediment volume. Much research has shown that kaolinitic soils usually occupy sediment volumes greater than 1.0 cm³/g in nonpolar carbon tetrachloride (Sridharan, A., Rao, S. M. and Joshi, S., 1990).

According to some physico-chemical concepts, it is evident that the expansiveness exhibited by a soil on contact with water is dependent on net electrical attraction forces. If weak repulsion prevails, little expansion may result. Conversely, if strong interparticle repulsion predominates, then high expansion may result. Tests involving sediment volume in carbon tetrachloride and water cover a wide range of expansivity characteristics. Furthermore, some kaolinitic soils may reach higher volumes in nonpolar solvents than in water because of flocculation in the nonpolar solvent.

In light of data from Tables 2.7 and 2.8, the present soil can be classified as nonswelling kaolinitic soil with negligible expansivity characteristics. Therefore, this

soil has no tendency for self-healing, which makes the soil more vulnerable to internal erosion.

Emerson (1964) observed that the two main causes for the breakdown of soil aggregates on immersion into water are: the compression of entrapped air and a decrease in the effective stress due to swelling. This behaviour may be a significant factor in the dispersion of partly saturated soils as previously mentioned in item 3.3.

3.8 Identification of dispersive clays

The dispersivity of a soil depends on its clay mineralogy and pore water chemistry. Soils with kaolinite or halloysite tend to be non-dispersive. Dispersion occurs in soils in which the repulsive forces between clay particles exceed the attractive forces so that, in the presence of relatively pure water, the particles repel each other and deflocculate to form a suspension. The mechanism by which dispersive soil erodes depends on the structure of the soil and the interactions between pore and eroding fluids. The principal conclusion reached by Sherard et al. (1976) is that the main factor governing soil dispersibility is the relative percentage of the pore water sodium content, as shown in Figures 2.4 and 2.5.

Low pore water salt content leads to a large diffuse ionic layer and has a greater potential for dispersion due to the net force of repulsion. Hence, percolation of a saline soil with fresh water may lead to dispersion.

Table 2.9 shows the results obtained from the SCS double hydrometer test used in this study to identify the susceptibility to dispersion of the soil in question.

According to this test, this soil had a low dispersion percentage of approximately 2.3 %.

SAR (Sodium Absorption Ratio) & TDS (Total Dissolved Salts)

The sodium absorption ratio is used to quantify the role of sodium when free salts are present in the pore water. The higher the SAR, the higher the concentration of sodium ions in the soil electrolyte system. Sodium ions have a lower valence than calcium and magnesium ions and, consequently, more sodium ions are required to satisfy the surface charge of the clay particles.

A particular problem which sometimes occurs in an embankment dam involves a change in pore water chemistry during reservoir filling. A change (decrease) in the salt concentration in the pore water may lead to the development of a large diffuse ionic layer together with a tendency toward dispersion. A soil which retains a flocculated structure during reservoir filling may become dispersive when exposed to reservoir water with a low salt content. The most useful criterion for determining whether a soil is dispersive or not is the simple chart (Fig. 2.5) developed by Sherard, et al. (1977). Sherard also defined three zones for classifying dispersivity:

(Zone 3). Much experience has shown that damaged and /or failed dams all over the world have been built with these dispersive soils, most of which were found to be dispersive in the pinhole test.

(Zone 5). Most of these soils are non-dispersive. These are generally thought to be ordinary dispersion-resistant clays, although their composition often includes silts of low plasticity (ML). A very small percentage of the soils in Zone 5 erodes in the pinhole test in exactly the same fashion as those in Zone 3, and some of these can only be identified via the pinhole test.

(Zone 4). Soils in this group may range from dispersive to non-dispersive. This group contains a few soils which have an intermediate reaction in the pinhole test and show apparent colloidal erosion at a much slower rate when compared to the Zone 3 soils.

Although the Atterberg limits do not provide a means of identifying potentially dispersive soils, those soils with higher plasticity indexes tend to afford greater resistance to dispersion. For instance, soils with a plasticity index higher than 35 % may swell to the extent that potential flow paths may be sealed before erosion proceeds too far (Sherard et al., 1977).

The potential dispersiveness of the soil studied is shown in Fig. 2.5. The percentage of sodium and TDS were obtained from lab tests and can be seen in Table 2.10. The value of Na is 58.77 % and of TDS is 1.1554, both of which are classified as zone 4 in the potential dispersiveness chart. Soils in this group may range from dispersive to non-dispersive. Therefore, because this soil retains a flocculated structure may become dispersive and susceptible to internal erosion when exposed to reservoir's water with a low salt content.

3.9 Permeability test using the triaxial cell apparatus

The results of the permeability tests show that the coefficient of permeability (k) of the Na-kaolinitic soil studied is dependent upon the fabric of the kaolinite in the mixture (kaolinite-silt). The intact samples tested were obtained from a hydraulic fill built with residual soils transported as slurry. Conditions at the time of deposition of the slurry determined the fabric of the kaolinite in the mixture, and this fabric controlled the permeability (k) of the soil studied. Permeability tests carried out by the author on this Na-kaolinitic soil at two different salinities showed that: a) By saturating this soil using deionized water (fresh-water) with a low pH the individual Na-kaolinite particles essentially expanded to the extent that the soil fabric could be characterized by an assemblage of positive edge-negative face flocculation. In this state the kaolinitic soil showed small permeability value; b) By using salt-water (20 mg /L of NaHCO_3) with a high pH the clay particle did not expand and the fabric was characterized by particles made up of tightly-bound sheets which created a barrier to particle flocculation. As expected, in this case, the kaolinitic soil showed a higher

permeability value. These results substantiate the view that the in situ soil fabric is characterized by an assemblage of positive edge-negative face flocculation.

Chapter 4

Conclusions

The conclusions reached regarding the behaviour of one of the thin interbedded layers of low-permeability clayey silt soils, in relation to internal erosion, are the focus of this chapter. The conclusions will be based on the internal erosion point of view, taking into account the following: a) the dominant clay mineral is Na-kaolinite, which is a residual clay derived from gneiss; b) this Na-kaolinitic soil ranges from dispersive to non-dispersive; c) the in situ soil fabric is characterized by an assemblage of positive edge-negative face flocculation; d) with dispersive soil, internal erosion is due to deflocculation process where water travels through a leakage channel, such as a crack; and e) the main concern is in regard to internal erosion during reservoir filling, because the layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts.

Conclusions

1) The soil making up the thin interbedded layer was originally a mature residual soil from Biotite Gneiss. This soil was transported by pump as slurry to form a hydraulic fill, which resulted in a soil deposit with complex and unique characteristics. The dominant clay mineral is kaolinite, which is believed to have a ≤ 5 cation exchange capacity (CEC). By way of the clayeyness degree index (0.95), it was possible to identify the presence of kaolinite with reasonable accuracy.

2) Atterberg limits were performed on specimens subjected to intensive cycles of remolding, a variety of pore-water chemistries, and alternate cycles of drying and wetting. A detailed analysis of the results demonstrated the relative importance of various soil composition factors and the soil fabric in controlling the liquid limit of

this Na-kaolinitic soil. The results also suggested that interparticle attraction and repulsion forces determined the soil fabric, which in turn controlled the liquid limit values. The presence of high valence cations and a low pore water environment pH promoted positive edge-negative face flocculation, while the presence of monovalent sodium ions and a high pH created a barrier to particle flocculation.

The influence of the geometric arrangement of clay particles (clay fabric) in regulating the liquid limit of this kaolinitic soil was confirmed based on the relationship between shrinkage limit and sedimentation volume values. This kaolinitic soil, which demonstrated a higher degree of particle flocculation and liquid limit, shrunk less and/or occupied a higher sediment volume when compared to a condition of lesser degree of particle flocculation (saturation with 20 g NaHCO₃/L). So, as expected, the increase in liquid limit was accompanied by an increase in shrinkage limit and sedimentation volume.

A low pore-water pH results in the liberation of cations of a higher order that collect on the surface of the clay particles, thereby raising the plasticity of the soil as well as making the soil less susceptible to internal erosion. This can only occur by continuously supplying pH-reducing agents to the clay. Cementing agents (organic matter, and aluminium and iron compounds) also lead to make the soil less susceptible to internal erosion.

3) Recent research has demonstrated that kaolinitic soil behaviour is affected by soil pH, exchangeable cation content, and interparticle forces, which, in turn, determine the soil fabric (see Sridharan et al., 1992). Results obtained in this study from the shrinkage limit test confirmed these findings. The shrinkage test results also indicated that, under actual field conditions, the soil has a flocculated particle arrangement and, consequently, undergoes less shrinkage upon drying.

4) Volumetric changes in the kaolinitic soil studied during air drying showed that this soil behaved as elastic material. Pore water pressures decreased when evaporation took place. Nevertheless, soil volume decreased due to the generation of negative pore-water pressures, which caused an increase in effective stresses. The volume decrease continued until the air-entry pressure had been reached. After reaching the air-entry pressure, the volume increased and when the soil was completely dry, ($u=0$) it attained the original saturated volume typical of elastic materials. The swelling induced a reduction in effective stress which, in combination with the developed air pressure in the voids, may possibly have caused the breakdown of the soil aggregates. This behaviour led to soil dispersion upon water immersion (re-wetting), which certainly increased the susceptibility of deflocculation and internal erosion.

5) The Clayeyness Degree x Plasticity relationship seems capable of providing a reasonably accurate identification of clay mineralogy, which is of significant importance in classifying residual soils as a whole. The combined Plasticity & Mineralogy Charts, elaborated by the author proved to be helpful in classifying residual soils. As referred to in section 3.6 of Chapter 3, it is impracticable to perform liquid limit tests on clay fractions of $< 2\mu\text{m}$. Therefore, it is suggested that the fine fraction $< 10\mu\text{m}$ be used. Consequently, the percentage $< 2\mu\text{m}$ of (Eq. 2.1), used to calculate C.D. should be replaced by the $< 10\mu\text{m}$ percentage. These new Plasticity & Mineralogy charts allow for a more realistic identification of this fine-grained soil by means of classifying its inherent properties. The above suggestion is based on experiments performed on a limited number of soil samples. In this connection, it would seem that further study is warranted at some later date.

6) Identification of expansive soils based on the sediment volume procedure is a reliable method of estimating soil expansivity. Laboratory tests showed that this Na-kaolinite soil settled rapidly, i.e., between 24 and 48 hours, to attain an equilibrium in

sediment volume. The presence of dissolved sodium in the pore-water (20g NaHCO₃/L) did not lead to a significant decrease in the time period required to attain an equilibrium in sediment volume. It was observed that the dissolved sodium (20g NaHCO₃/L) caused a decrease in sediment volume when compared to the results obtained from fresh-water (deionized) in this type of soil. In light of data from Tables 2.7 and 2.8 the present soil can be classified as nonswelling kaolinitic soil with negligible expansivity characteristics. In this case, the soil has no tendency for self-healing, which means that if the initial velocity of a concentrated leak is above a threshold value, the clay particles surrounding the flow channel are carried away, enlarging the flow channel at a faster rate than it is closed by swelling, leading to progressive internal erosion.

7) The dispersivity of a soil depends on its clay mineralogy and on its pore-water chemistry. For example, percolation of Na-kaolinite with fresh-water may lead to dispersion. Double hydrometer tests (SCS) showed the present soil to have a low dispersion rate (2.3 %). The Sodium Absorption Ratio (SAR) confirmed that this soil had no dispersive characteristics (see Sherard, 1977). On the other hand, Sherard's Potential Dispersiveness Chart indicated that this soil ranged from dispersive to non-dispersive.

A decrease in the concentration of salts in the pore water may lead to a large diffuse ionic layer and a tendency toward dispersion. As the present soil retains a flocculated structure during reservoir filling may become dispersive when exposed to reservoir water with low salt content. Therefore, the kaolinitic layer in study is susceptible to deflocculation and internal erosion.

8) The results of permeability tests showed that the coefficient of permeability (k) of the Na-kaolinitic soil studied is dependent upon the fabric of the kaolinite in the mixture (kaolinite-silt). In addition, the results substantiated the view that the in situ soil fabric is characterized by an assemblage of positive edge-negative face flocculation.

The present study has shown that the main concern is in regard to internal erosion during "Lajes Reservoir" filling, because the Na-kaolinitic layer in study is susceptible to deflocculation when saturated by water with low total content of dissolved salts.

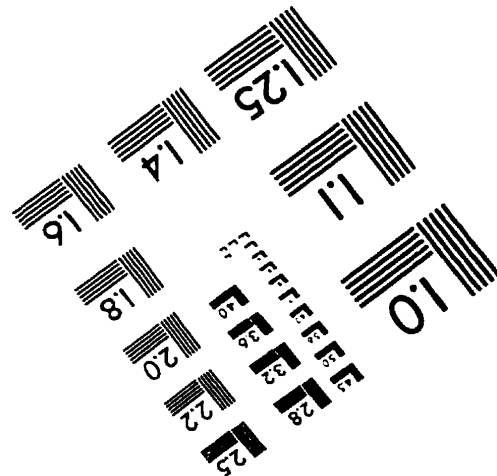
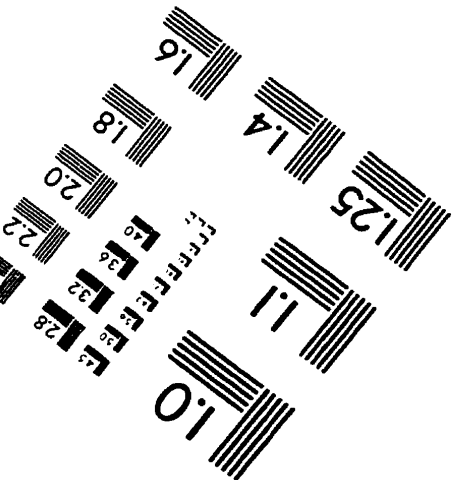
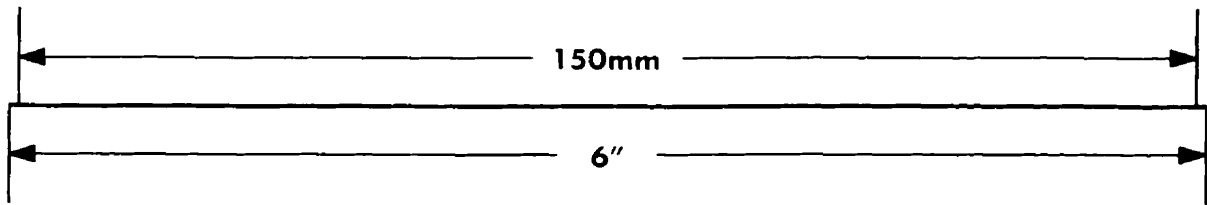
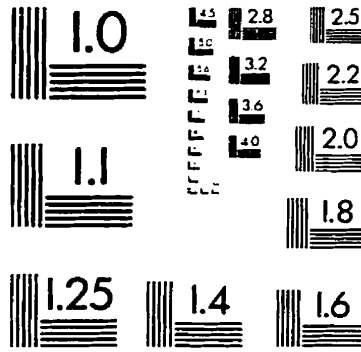
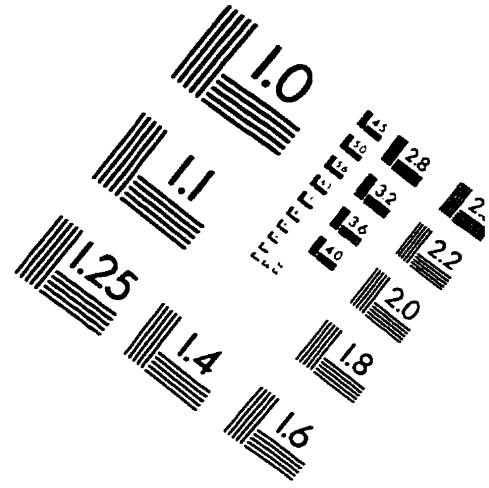
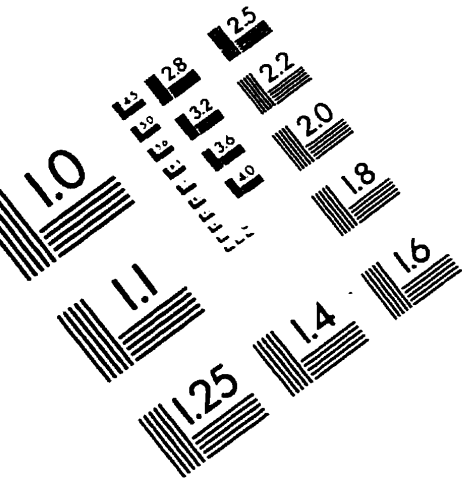
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IMAGE EVALUATION TEST TARGET (QA-3)



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