Anisotropic behaviour of clay core, foundation, and clay blanket in existing earth fill dams

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ABSTRACT
Anisotropic behaviour of clay core, blanket, and foundation in earth fill dams may be a result of environmental loading such as wetting-drying and freeze-thaw cycles. The depositional process of the foundation soil and the compaction of clay core and clay blanket may also play a significant role in its anisotropic behaviour. This paper presents the drilling, sampling and testing program in the existing earth fill dams. It also presents the results from laboratory tests that include Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), one-dimensional consolidation oedometer tests, direct shear tests, and isotropically consolidated undrained triaxial tests. The laboratory results would be used to investigate the operating mechanisms of slope movements in an existing earth fill dam.

RÉSUMÉ
Le comportement anisotrope du noyau d'argile, de la couverture et de la fondation dans les barrages en terre peut être le résultat de charges environnementales telles que les cycles de mouillage-séchage et de congélation-décongélation. Le processus de dépôt du sol de fondation et le compactage du noyau d'argile et de la couverture d'argile peuvent également jouer un rôle important dans son comportement anisotrope. Cet article présente le programme de forage, d'échantillonnage et d'essais dans le barrage en terre existant. Il présente également les résultats d'essais en laboratoire qui comprennent la microscopie électronique à balayage et la diffraction des rayons-X, les tests de consolidation unidimensionnels, les essais de cisaillement direct et les essais triaxiaux non drainés consolidés isotropes. Les résultats de laboratoire seraient utilisés pour étudier les mécanismes de fonctionnement des mouvements de pente dans un barrage en terre existant.

1 INTRODUCTION

Anisotropy was one of the factors that influence the prediction of embankment performance (Graham 1979). Anisotropy in structural composition, mechanical behavior, and shear strength of Lake Agassiz clays had been studied extensively by different researchers (e.g. Baracos 1977; Freeman and Sutherland 1974; Graham and Houlsby 1983; Graham 1979; Loh and Holt 1974).

Baracos (1977) examined the compositional and structural anisotropy of Winnipeg soils using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD). Baracos reckoned that differences in composition between dark colored *(clay minerals)* and light colored *(non-plastic, non-clay minerals)* constituents are major causes of anisotropy. Light colored and horizontally oriented varves, veins, and seams contribute to greater horizontal permeability, planes of different strength, and ease of cleavage along horizontal planes. Some layers of clay have a microstructure of mostly horizontally oriented clay particles, with much edge-to-edge bonding, which further contribute to the observed anisotropy. The structural and compositional anisotropy further contribute to the anisotropic elastic behavior of clays during shearing. Lake Agassiz clays are also reported to have horizontal stiffness 1.8 times greater than its vertical stiffness (Graham and Houlsby 1983). Freeman and Sutherland (1974) had conducted detailed laboratory testing to assess the anisotropic strength properties of the clays by doing triaxial testing ($CI\bar{U}$ and CID) on specimens trimmed in various orientations. Test results showed that that the shear strength envelopes along the layers were lower than that shear strength envelopes across the layers. Other researchers had also studied the anisotropic undrained shear strength and deformation behavior of Lake Agassiz upper brown clay. Study by (Loh and Holt 1974) reckoned that anisotropic clay fabric and stratification causes anisotropy in undrained shear strength of the clay.

Cyclic expansion and contraction of clays due to wetting-drying and freezing-thawing can also cause anisotropy in clays. Environmental loading creates fissures resulting to anisotropy in its mechanical behavior. These fissures create planes with weaker strength and higher permeability (McGown and Radwan 1975).

Research is currently ongoing to evaluate the stability of earth dams in hydroelectric generating stations as part of its periodic dam safety review. There are concerns about possible deterioration of clay foundation, core and blanket due to environmental loading. Environmental loadings such as wetting-drying and freezing-thawing can produce fissures and anisotropy of clays (Baracos 1977; Graham and Houlsby 1983). Fissures could alter the flow, deformation and shear strength characteristics of these materials. The research will help in evaluating the current slope stability of earth fill dams (embankment dams) at four hydroelectric generating stations. It will also help in evaluating long-term performance of earth dams and in carrying out proactive rehabilitation if their performance does not meet current dam safety standards.

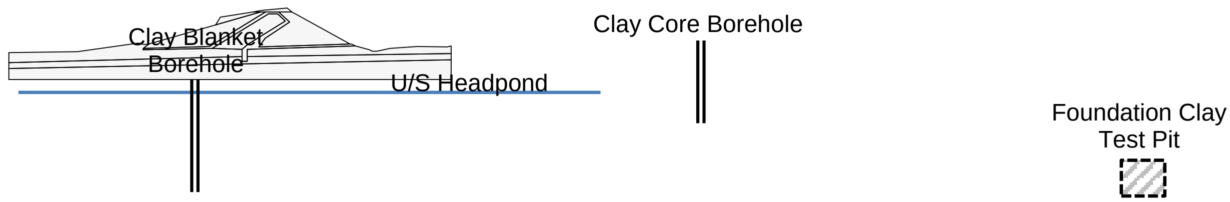

Figure 1. Typical cross – section of dam showing borehole and test pit locations for sampling.

This paper presents the soil sampling and preliminary laboratory tests done to assess the anisotropic properties of clay core, foundation clay, and clay blanket of an aging earth fill dam.

2 DRILLING AND SOIL SAMPLING

Following a preliminary assessment done on the dam of interest, drilling and undisturbed soil sampling were completed during the fall season when the ground was still unfrozen. Continuous soil sampling by means of a Hollow Stem Auger (HSA) using Shelby tubes with a diameter of 102mm (4in) was used to collect clay core and foundation clay samples from predetermined borehole locations. Figure 1 shows a typical cross-section of the dam including the locations of boreholes and test pit.

In a test pit, Shelby tube soil samples were also obtained. These samples have two orientations: vertical or inclined. Vertical Shelby tube samples were simply pushed perpendicular into the test pit floor. Inclined Shelby tube samples were pushed into the wall of a test pit with an angle of inclination of 53° from the horizontal, as shown in Figure *2*. Inclined samples were collected to determine the horizontal shear strength by performing isotropically-consolidated undrained triaxial compression tests (CI$\overline{\text{U}}$).

Samples from the clay blanket were taken during the winter season. Offshore drilling was done over the frozen reservoir in order to obtain clay blanket samples using a piston sampler with a diameter of 76.2mm (3in).

Figure 2. Shelby tube samples with inclined orientation

3 EXPERIMENTAL INVESTIGATION

A laboratory testing program was carried out to further investigate the anisotropic behaviour of the collected clay core and foundation samples. Several tests were conducted to determine the index properties, mineralogy, strength, and deformation characteristics of the collected samples.

3.1 Index Property Tests

Index properties and deformation characteristics are shown in Table 1. Deformation characteristics were based on one-dimensional consolidation (oedometer) test results.

Table 1. Characteristics of tested soils

Sample	Clay Core	Clay Foundation	Clay Blanket
Moisture Content (%)[1]	39	38	41
Liquid Limit (%)	85	89	82
Plasticity Index (%)	60	61	57
Specific Gravity, *Gs*	2.72	2.70	2.68
Minus #200, <0.075mm (%)	100	100	100
Clay Fraction, <0.002mm (%)	74	75	71
Activity	0.81	0.81	0.80
Apparent preconsolidation pressure (kPa)	150	200	170
Slope of NCL, λ	0.125	0.124	0.145
Slope of NCL, κ	0.024	0.028	0.042

[1]moisture content of specimens after preparation

3.2 Scanning Electron Microscopy Test

Prepared carbon coated soil specimens were examined using FEI Inspect S50 Scanning Electron Microscope (SEM) with back-scattered electron and Energy Dispersive X-ray (EDX) system. An SEM image of clay particles from the clay foundation (Figure 3) show predominantly edge-to-edge contacts with random non-clay particles for specimens at lower depths without a preferred alignment or orientation with some micro fissures between flocs. Clay core samples (Figure 4) are more flocculated which are also separated by micro fissures. The top layer of the clay blanket (Figure 5) shows an edge-to-edge contact and slight particle alignment whereas the bottom layer (Figure 6) shows most particles forming broad overlapping sheets.

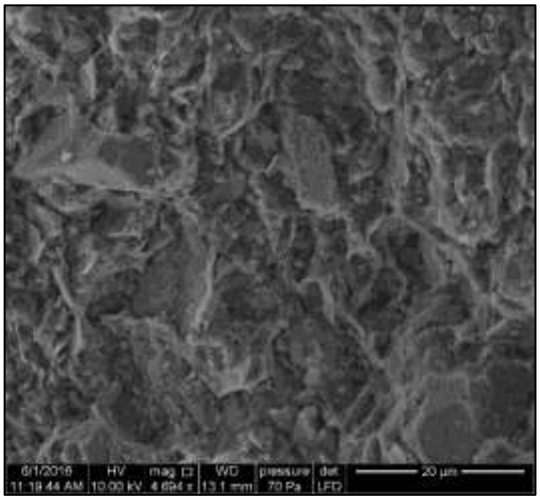

Figure 3. SEM image of clay foundation.

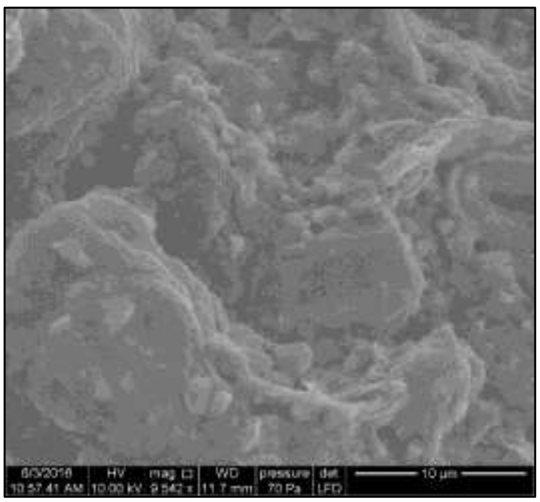

Figure 4. SEM image of clay core.

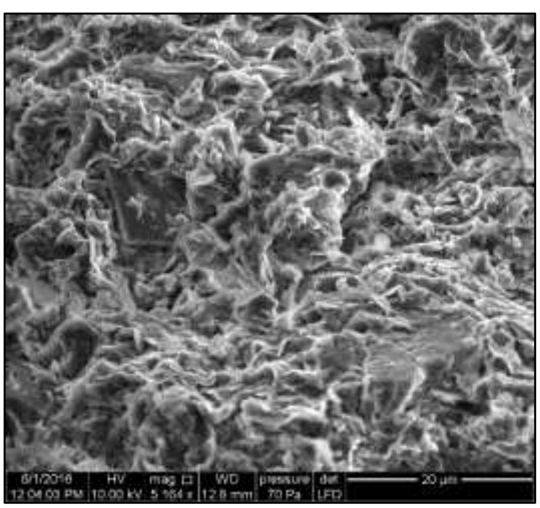

Figure 5. SEM image of clay blanket (top layer)

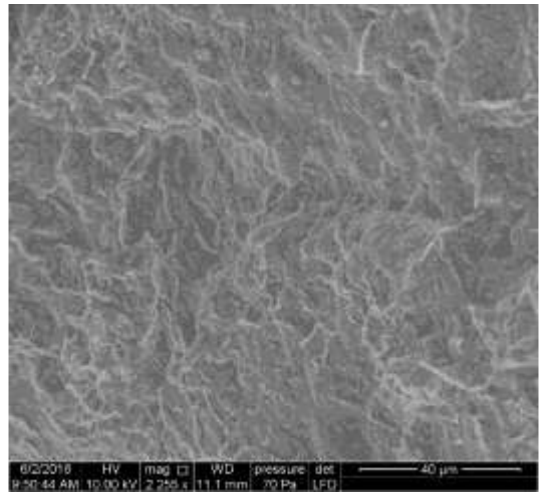

Figure 6. SEM image of clay blanket (bottom layer)

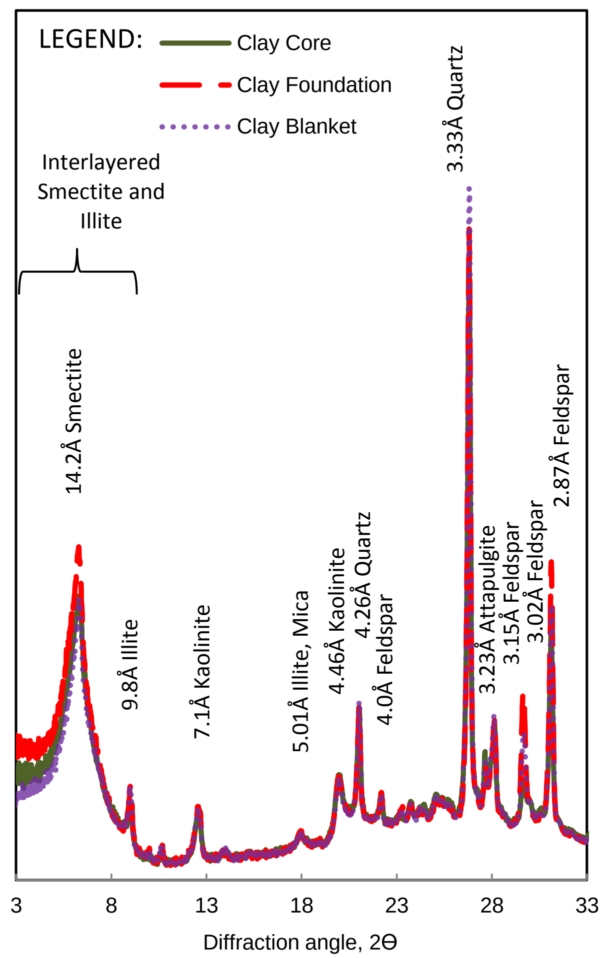

Figure 7. X-ray diffraction patterns from powdered specimens.

3.3 X-ray Diffraction Test

The strength of clay is known to be affected by its mineralogy. X-ray diffraction (XRD) testing was performed to determine the mineralogical composition of the clay and non-clay constituents of the samples. Samples obtained for XRD testing were dried and pulverized. Due to the presence of whitish silt pockets, pulverized samples were not sieve to include non-clay minerals in the analysis. Dry powder specimens were prepared following the procedure described by Mitchel (1956).

Figure 7 shows XRD results from clay core, foundation, and blanket. All samples show the same mineralogical composition. Clay minerals present are mostly interlayered smectite and illite with some kaolinite and mica and traces of attapulgite. Non-clay minerals are composed of quartz, feldspar, and dolomite.

The clay was thought to be an expansive type as the dominant clay mineral was smectite. Observed non-clay minerals such as quartz and feldspar are typical composition of silt, consistent with the observed of silt pockets. Similar findings were also reported by Baracos (1977) found in his study on Winnipeg clays (Lake Agassiz clay) and by Loh and Holt (1974).

3.4 Drained and Undrained Shear Tests

To determine the anisotropy in strength, multi-directional shearing tests were conducted. For clay core and clay blanket test specimens, cross-shear strengths were determined by means of isotropically-consolidated undrained triaxial compression tests (CI$\bar{U}$) and horizontal shear strengths were determined by means of consolidated-drained direct shear testing. For clay foundation soils, specimens taken from vertical Shelby tube samples determined cross shear strengths from isotropically-consolidated undrained triaxial compression tests. Inclined Shelby tube samples of clay foundation that underwent CIU testing provided horizontal shear strength values. Residual shear strengths for clay core, blanket, and foundation samples were taken from drained direct shear tests. As part of the experimental investigation on the effects of fissures to the anisotropy in strength, all specimens prepared for CI$\bar{U}$ testing had a specimen height to diameter ratio of 2:1 and a diameter of 71.12 cm.

Undrained shear testing results are shown in Figure 8, *Figure* 9, and Figure 10 for clay core, foundation, and blanket samples, respectively. It could be observed in Figure 8 that clay core samples sheared at a mean effective stress between 100 kPa to 300 kPa show an isotropic elastic behaviour ($m\Delta p \approx \Delta u$). Slight anisotropy was observed when the clay core was shear under a low confining stress (less than 100 kPa) which could be due to the tendency of fissured materials to dilate. Specimens sheared higher than 300 kPa behaved typically for a normally consolidated specimen. Both vertical and inclined foundation clay samples show elastic anisotropy as shown in Figure 9. Inclination of stress paths to the left (m>1) indicated that the sample had higher horizontal stiffness than its vertical counterpart. Similar behaviour was observed in CIU clay blanket samples (Figure 10). Samples sheared greater than 400 kPa were normally consolidated whereas the rest were over-consolidated samples.

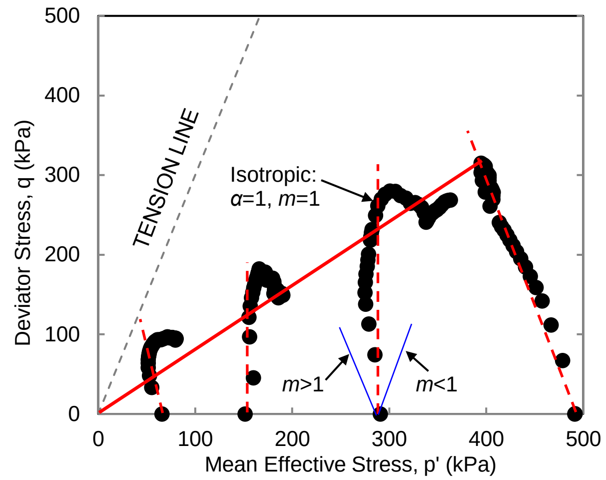

Figure 8. Estimated strength parameters from CIU tests on clay core samples.

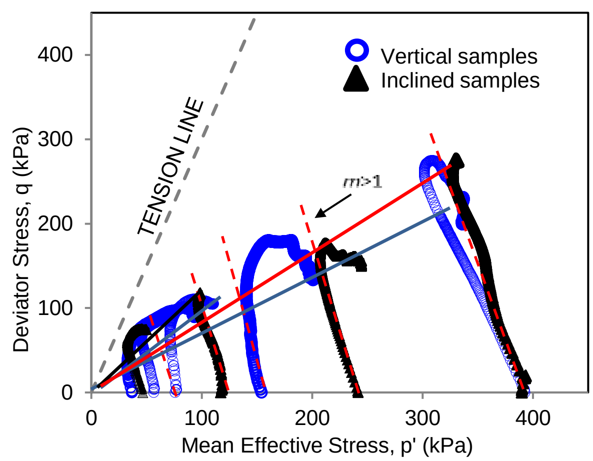

Figure 9. Estimated strength parameters from CIU tests on inclined and vertical clay foundation samples.

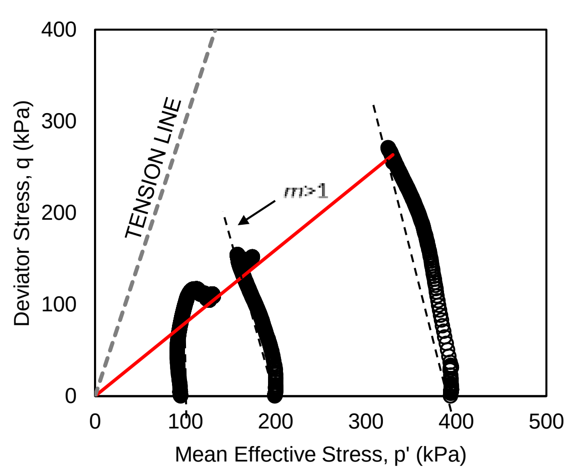

Figure 10. Estimated strength parameters from CIU tests on clay blanket samples.

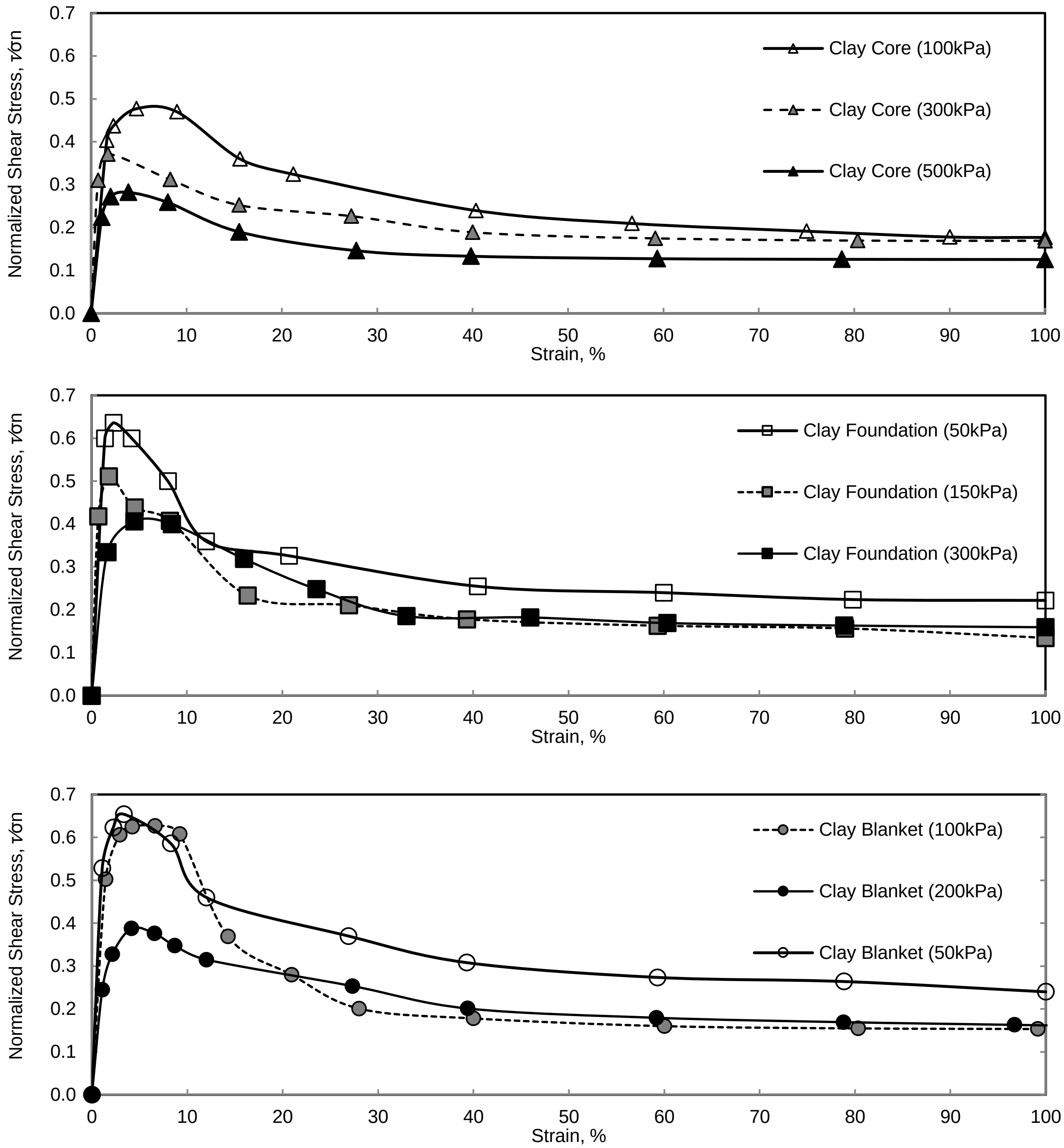

Figure 11. Stress – strain behavior from consolidated drained direct shear tests.

Table 2. Summary of estimated strength parameters

Stress Range	Clay Core		Clay Foundation		Clay Blanket	
	Cross Shear φ' (deg)	Horizontal Shear φ' (deg)	Cross Shear φ' (deg)	Horizontal Shear φ' (deg)	Cross Shear φ' (deg)	Horizontal Shear φ' (deg)
Stress < 100 kPa	19	13	24	29	21	17
Stress > 100 kPa	19	13	18	16	21	17
Residual Strength	--	8	--	7	--	9

The clay core and clay blanket results in CIU also exhibited a more uniform failure envelope as compared to the clay foundation. The foundation, on the other hand, exhibited a bilinear failure envelope. Higher frictional resistance was observed for stresses less than 100kPa and decreased as the confining stress increased. The bilinear failure envelope was thought to be attributed to the intense fissuring of the clay foundation, resulting to an increase in dilatancy under lower stress levels (Yoshida, Morgenstern, and Chan 1991).

The stress – strain behavior from drained shear strength test results conducted on all samples are seen in Figure 11. All samples exhibited brittle behaviour under low normal stresses and became ductile with the increase of applied normal stresses. The foundation clay and clay blanket behaved similarly as both underwent strain softening as compared to the clay core. This behaviour could be attributed to the fissured nature of the clay blanket and foundation.

Cross-shear and horizontal shear strength parameters were interpreted using Critical State Soil Mechanics (CSSM) approach and were summarized in Table 2. Results show that strength anisotropy is evident having cross shear strength values different that horizontal shear strength in all tested clay. Clay core and blanket samples have higher cross shear strength than that along the horizontal shear plan and the values are independent of the stress range. Foundation clay results show that in addition to anisotropic strength, shear strength values were dependent on the stress range. This indicates a bilinear failure envelope for both cross shear and horizontal shear. For both directions, the shear strengths were higher and decreased as the confining stress was increased. In addition, as the confining stress was increased, strength anisotropy seemed to have decreased as the difference in shear strength values have decreased. As previously mentioned, such bilinear failure envelope could be due to the dilatancy behaviour of the intensely fissured clay foundation.

4 SUMMARY

During drilling and soil sampling, it was observed that both the clay core, clay foundation and clay blanket soil had fissured structures. The clay foundation was also observed to have more intense fissuring and more silt pockets as compared to the others. Even with the difference in the degree of fissuring, all samples can be considered as similar based on determined index properties and examination of its structural and mineralogical composition. All samples have similar composition with clay minerals which of mostly interlayered smectite and illite. Non-clay minerals were mostly feldspar and quartz. The micro fabric clay was anisotropic, shown as an interlayered smectite and chlorite. The presence of silt pockets also could also result to anisotropic behaviour of the foundation soil in general such as in terms of strength and permeability.

CIU tests on clay core samples show isotropic elastic behavior but shows slight anisotropy when sheared under low confining stress. This slight anisotropic behavior could be due to the fissured nature of the soil which allowed it to dilate. Both vertical and inclined clay foundation samples that were used for CIU tests revealed elastic anisotropic behavior. Inclination of stress paths to the left ($m>1$) indicated that the sample had higher horizontal stiffness than its vertical counterpart. Similar behaviour was observed in CIU clay blanket samples.

Anisotropy in strength is also evident in all tested clay samples having different cross shear and horizontal shear strength values. Clay core and clay blanket samples have higher cross shear strength than that along the horizontal shear plane.

Results show that other than anisotropy in its mineralogical composition, the undrained and drained strength of the materials used in construction of old earth fill dams are anisotropic. Intense fissuring of the clay foundation resulted to a bilinear failure envelope of the clay. The clay core and clay blanket on the other hand, though slightly fissured did not result to a bilinear failure and had a more uniform failure envelope. Further investigation is still being conducted and results will be used to evaluate the long-term performance of earth dams and to carry out proactive rehabilitation if their performance does not meet current dam safety standards.

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