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STABILITY ASSESSMENT OF AN AGING EARTH FILL DAM CONSIDERING ANISOTROPIC BEHAVIOUR OF CLAY

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ABSTRACT: Anisotropic behaviour of the clay core, blanket, and foundation of aging water retaining earth fill dams on glacio-lacustrine clay deposits in Canada may be a result of environmental loading. The repeated wetting-drying and freezing-thawing cycles produce fissures that can cause degradation of strength with time. Undisturbed clay samples taken from field investigations of an existing aging water retaining earth fill dam were tested in the laboratory to obtain the parameters used in the numerical modeling. A testing program was implemented in order to determine the basic soil properties along with mineralogy, strength, and deformation characteristics of the collected clay samples. Laboratory tests include index property tests, Scanning Electron Microscopy (SEM) tests, X-Ray Diffraction (XRD) tests, one-dimensional consolidation oedometer tests, consolidated drained direct shear tests, and isotropically consolidated undrained triaxial compression tests. Results revealed that the clay samples from the clay core, blanket and foundation were similar in terms of structural and mineralogical composition. The observed interlayered smectite and illite indicated that the micro fabric was anisotropic. Strength anisotropy was noticed as results had different cross shear and horizontal shear strength values. Numerical modeling was performed to assess the slope stability of an aging earth dam that experienced sliding movements using parameters from the completed laboratory investigation. Findings from slope stability analyses indicated that a better representation of the observed site conditions was evident when strength anisotropy was considered.

Keywords: Anisotropy, Earth fill dam, Stability, Clay core, Clay blanket

1. INTRODUCTION

Anisotropic soils have directionally dependent properties. Anisotropy is sometimes referred to as the difference of a physical soil property along different directions. Most natural clay has a particle arrangement or fabric that is initially anisotropic due to its platy particle shape and deposition process. Repeated expansion and contraction of clays due to wetting-drying and freezing-thawing can also cause fissures leading to mechanical anisotropy. Fissures tend to create planes of weaker strength and higher permeability in clays [1].

The foundation soil in parts of Canada is glacio-lacustrine clay left by proglacial Lake Agassiz. As ice sheets melted northwards, runoff formed a large lake in what are now Manitoba, northwestern Ontario and northeastern Saskatchewan in Canada; and eastern North Dakota, and western Minnesota, both of which are US states. At its largest extent, Lake Agassiz was larger than all of the current Great Lakes combined [2].Anisotropy in structural composition, mechanical behavior, and shear strength of Lake Agassiz clays had been studied extensively by different researchers and was thought to influence embankment performance [3-7].

Despite the increasing awareness of anisotropy in geotechnical engineering, conventional geotechnical design approach would typically describe soil as isotropic due to convenience or lack of information [8]. In addition, the degree of accuracy of the material properties used as input data would affect the credibility of the results of numerical modeling [9]. Due to this, it is necessary to determine suitable testing methods that would provide the approriate parameters to be used in anisotropic-based analyses.

Research was carried out to evaluate the stability of earth dams in hydroelectric generating stations considering anisotropic behaviour as part of its periodic dam safety review. It will also aid in carrying out proactive rehabilitation, if the performance does not meet current dam safety standards. This paper presents the stability assessment of an aging earth dam that experienced sliding movements considering clay anisotropic behaviour using parameters determined from laboratory tests performed on undisturbed samples taken from field investigations.

2. SITE INVESTIGATION AND SOIL SAMPLING

The study focused on an aging water-retaining earth fill dam with an upstream inclined clay core that was constructed in the 1950s. The local clay material used in the construction of the dam was classified as high plasticity lacustrine clay, often described as highly fissured in nature with nuggetty appearance.

Undisturbed soil sampling of the clay core and foundation 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 102 mm (4 in) was used to collect samples from predetermined borehole locations.

Shelby tube samples of the clay foundation were obtained from test pits. These samples have two orientations: vertical and 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 Fig.1. The inclination would provide horizontal shear strength values when the samples were tested in triaxial apparatus.

Fig.1 Shelby tube clay foundation sample with inclined orientation

Soil sampling of the clay blanket was done during the winter season as the frozen reservoir allowed the drilling equipment to be appropriately positioned over borehole locations. Typical 76 mm (3 in) diameter Shelby tubes on a track-mounted piston sampler was used to collect clay blanket samples. Multi-directional sampling of the clay core and blanket were not performed to reduce further disturbance in these locations.

Figure 2 shows the cross-section of the earth dam with typical sampling locations.

3. EXPERIMENTAL INVESTIGATION

Several laboratory tests were conducted to determine the index properties, deformation characteristics, mineralogy, and strength characteristics of the collected clay core, blanket, and foundation samples. Tests were in accordance with ASTM standards.

3.1 Index Properties and Deformation Characteristics

The index properties of the tested samples are shown in Table 1. Extruded clay core samples were a mottled mix of brown and grey with random silt lenses and silt pockets. It had a matted texture with medium to stiff consistency. Clay blanket samples were brown in color, with soft to medium consistency in the upper layer; and mottled mix of brown and grey with stiff to very stiff consistency from 0.6 m and below. The clay foundation samples were mottled mix of brown and grey in color with random silt pockets and was intensely fissured. All tested samples were classified as “fat clay” of high plasticity (CH) according to the Unified Soil Classification System (USCS). Deformation characteristics, also in Table 1, were based on one-dimensional consolidation (oedometer) test results.

3.2 Particle Orientation and Mineralogy

Mechanical properties of soil could be influenced by its microstructure [10]. Microscopic anisotropy could be due to differences in particle orientation and mineralogy.

Scanning Electron Microscope (SEM) was used to examine the particle orientation of the prepared carbon coated specimens. SEM images of the clay core (Fig.3) displayed an edge-to-edge contact and slight particle orientation whereas clay blanket samples (Fig.4) showed that most particles formed broad overlapping sheets. Images of clay foundation samples (Fig.5) show predominantly edge-to-edge contacts with random non-clay particles without a preferred alignment or orientation.

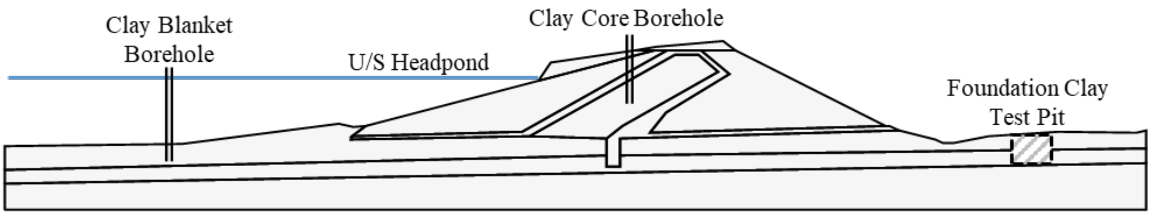

Fig.2 Typical borehole and test pit sampling locations

Table 1 Soil properties of tested samples

Properties	Clay Core	Clay Blanket	Clay Foundation
Moisture content (%)	39	41	38
Liquid limit (%)	85	82	89
Plasticity index (%)	60	57	61
Specific gravity	2.72	2.68	2.70
Minus #200, <0.075mm (%)	100	100	100
Clay fraction, <0.002mm (%)	74	71	75
Activity	0.81	0.80	0.81
Apparent preconsolidation pressure (kPa)	150	170	200
Slope of NCL, λ	0.125	0.145	0.124
Slope of NCL, κ	0.024	0.042	0.028

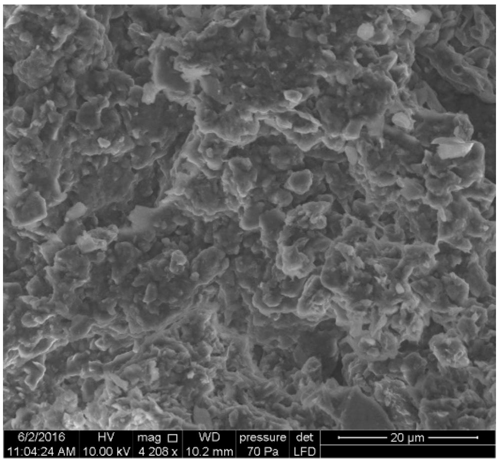

Fig.3 SEM image of clay core.

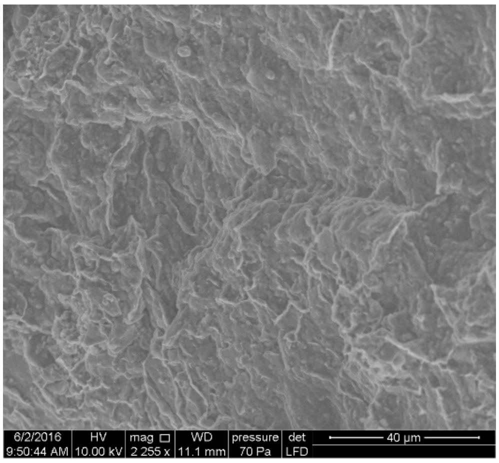

Fig.4 SEM image of clay blanket.

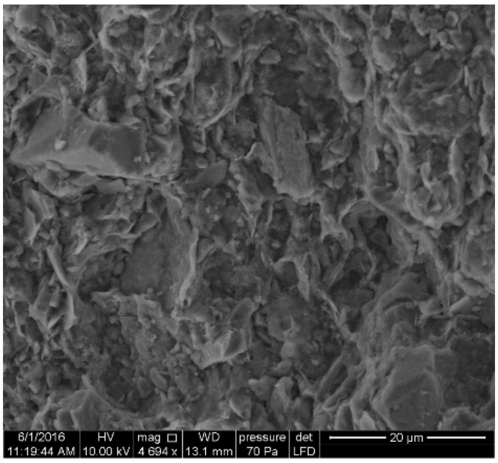

Fig.5 SEM image of clay foundation.

X-ray diffraction (XRD) testing was performed to determine the mineralogical composition of the clay and non-clay constituents of the samples. Figure 6 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, 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 [3] found in his study on Lake Agassiz clay and by Loh and Holt [7].

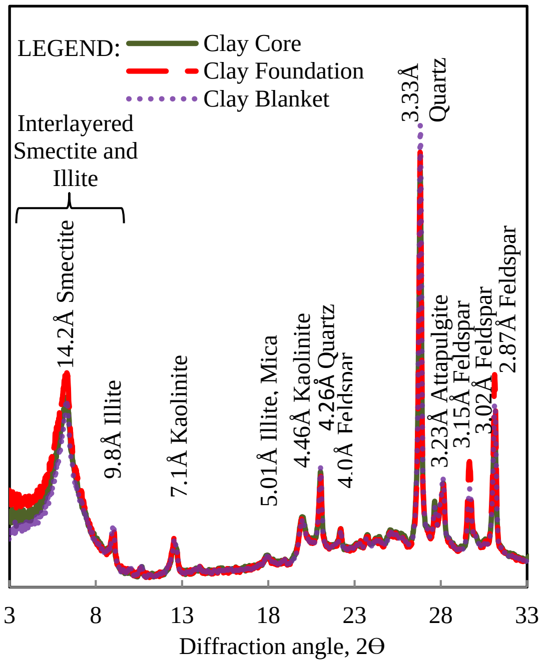

Fig.6 XRD results from clay core, blanket, and foundation.

3.3 Shear Strength Parameters

Multi-directional shearing tests were conducted to determine strength anisotropy. Vertical clay foundation Shelby tube samples determined cross shear strengths from isotropically consolidated undrained triaxial compression (CIU) tests. Inclined Shelby tube samples of clay foundation that underwent CIU testing provided horizontal shear strength values. For clay core and clay blanket test specimens, cross-shear strengths were determined from CIU tests. As it was not possible to obtain inclined samples from the clay core and blanket, horizontal shear strengths were determined by means of consolidated drained (CD) direct shear testing from vertical Shelby tube clay foundation samples. Residual strengths were determined from direct shear tests. Multiple reversal method was used wherein clay samples were repeatedly sheared until 100 % strain was reached, which corresponded to about 63 mm of displacement.

Undrained shear testing results are shown in Fig.7, Fig.8, and Fig.9 for clay core, blanket, and foundation samples, respectively. Stress paths during undrained shearing would imply isotropic elastic behaviour if the initial slope before failure (m) would be equal to 1. This would mean that the changes in pore water pressure (Δu) corresponds to the changes in the mean total stress (Δp) for isotropic soil ($m\Delta p \approx \Delta u$), and otherwise for anisotropic soil ($m\Delta p \neq \Delta u$) [5]. Figure 7 shows that clay core samples sheared at a mean effective stress between 100 kPa to 300 kPa exhibit an isotropic elastic behaviour (m=1), with a slight anisotropy observed when the clay core was sheared under a lower confining stress less than 100 kPa. This could be due to the tendency of fissured materials to dilate. Clay blanket samples also show slight elastic anisotropy as seen in Fig.8. Both vertical and inclined clay foundation samples show elastic anisotropy as shown in Fig.9. Inclination of stress paths to the left (m>1) indicated that the sample had higher horizontal stiffness than its vertical counterpart [5,11,12]. Specimens sheared higher than 300 kPa behaved typically for a normally consolidated specimen.

The clay core and blanket CIU results exhibited a more uniform failure envelope compared to the clay foundation, which exhibited a bilinear failure envelope. Higher frictional resistance was observed for confining 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 leading to an increase in dilatancy under lower stress levels [13].

The stress-strain behavior from drained shear strength test results conducted on all samples is seen in Fig.10. 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.

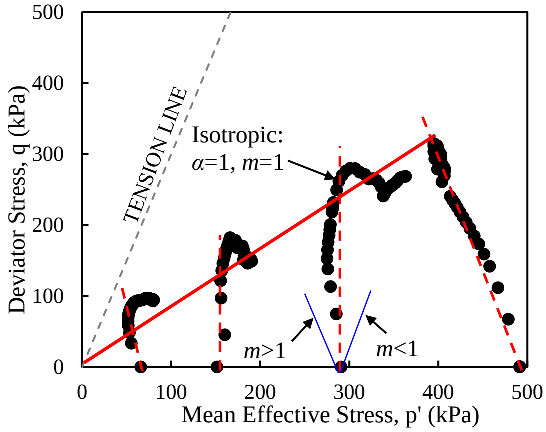

Fig.7 Clay core CIU triaxial test results.

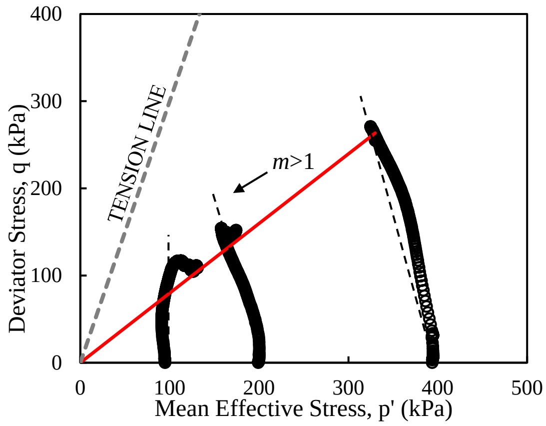

Fig.8 Clay blanket CIU triaxial test results.

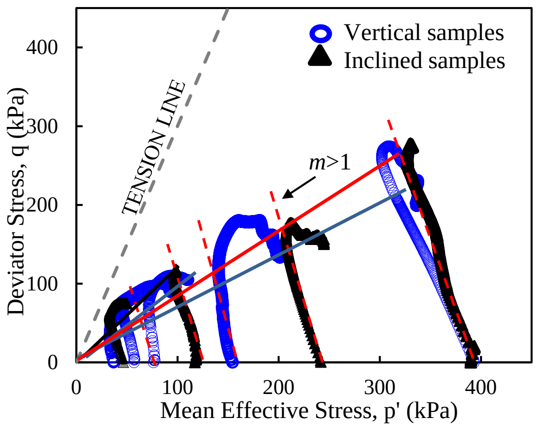

Fig.9 Clay foundation CIU triaxial test results.

Cross-shear and horizontal shear strength parameters were interpreted using Critical State Soil Mechanics (CSSM) approach and summarized in Table 2. Strength anisotropy is evident having different values between cross shear strengths and horizontal shear strengths in all tested clays. Clay core and blanket samples have higher cross shear strengths than that along the horizontal shear plane and the values are independent of the stress range. Clay foundation results show that in addition to anisotropic strength, shear strength values were dependent on the stress range, which indicated a bilinear failure envelope. For both cross shear and horizontal shear, the strengths were higher at a lower confining stress and decreased as the confining stress was increased. Strength anisotropy seem to decrease as the confining stress increased as expressed in the decreased difference in shear strength values. The bilinear failure envelope could be once again due to the dilatancy behaviour of the intensely fissured clay foundation.

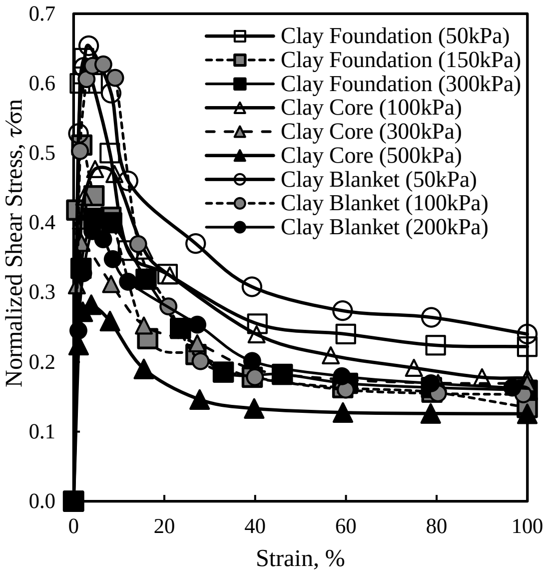

Fig.10 Stress-strain behavior from CD direct shear tests.

Table 2 Summary of estimated effective shear strength parameters

Stress Range (kPa)	Clay Core CS	Clay Core HS	Clay Blanket CS	Clay Blanket HS	Clay Foundation CS	Clay Foundation HS
<100	19	13	21	17	24	29
>100	19	13	21	17	18	16
Residual		8		9		7

Note: CS = cross shear, φ' (°), HS = horizontal shear, φ' (°)

4. NUMERICAL MODELING

Numerical modeling was implemented using the GeoSlope program suite in order to evaluate the stability of the earth fill dam using a 2-dimensional plane strain model. The location of the phreatic surface was determined using the steady-state seepage analysis in the finite element program, SEEP/W and was confirmed by readings from vibrating wire piezometers installed on site. Stress distribution method was performed using the finite element program, SIGMA/W to establish in-situ stresses conditions. Results from the stress distribution and seepage analysis were imported in the SLOPE/W slope stability analysis, which is based on limit equilibrium method.

The dam of interest has two sections, depending on the foundation conditions. Section A has a clay foundation that stretches from the upstream to the downstream side of the dam, overlying dense silty sand. Section B has an absence of an impermeable natural clay layer with only a layer of dense silty sand and gravely sand underneath the dam. In order to control seepage in this section, a compacted clay blanket was placed in the upstream side and was tied into the inclined clay core. Movement was observed in the upstream section of Section B despite its good performance for over fifty years.

Post peak or critical state shear strength parameters were used in the numerical modeling as the clay materials in the dam were thought to have reached its fully-softened condition over the years. Cohesion was assumed to be zero for fully softened shear strengths of fissured clays [14]. Two cases of slope stability analyses were conducted. Case 1 considered the anisotropic strength model for clay materials to simulate the difference in strength along the cross-shear and horizontal direction. Case 2 used the Mohr-Coulomb strength model. Based on the shape of the postulated slip surface, cross-shear strength values were assigned to the clay core whereas the clay blanket used horizontal shear strength values. Clay foundation horizontal shear strengths were inputted using a bilinear soil model for Case 2. Input parameters used in the numerical modeling can be seen in Table 3.

Table 3 Input parameters for numerical modeling

Parameters	Clay Core	Clay Blanket	Clay Foundation
γ (kN/m^3)	17	17	17
υ	0.35	0.45	0.35
λ	0.125	0.145	0.124
κ	0.024	0.042	0.028
c' (kPa)	0	0	0
$\Phi'_{cross\text{-}shear}$ (°)	19	21	18
$\Phi'_{horizontal}$ (°)	13	17	16
$\Phi'_{bilinear}$ (°)	n/a	n/a	29,16

The results of the SLOPE/W slope stability analyses are presented in Table 4. The results were compared to the following dam safety criteria: a factor of safety (FS) of 1.5 against normal water level load cases, and a value of 1.0 considering normal water levels and seismic loading. The calculated factors of safety indicate that the use of anisotropic soil analysis (Case 1) tend to generate lower values for both dam sections compared to Case 2. Results also show that the upstream slope was more critical than the downstream side for both sections of the dam using either Case 1 or 2, primarily due to the geometry of the inclined core. Moreover, the upstream side of Section B had a factor of safety value less than unity (FS = 0.99) when anisotropy was considered. This corresponds to the observed sliding movement in this section. It is evident that the upstream slope does not pass the safety criteria, with Section B as the most critical. The critical upstream slope stability results for both Sections A and B using Case 1 can be seen in Fig.10 and Fig.11, respectively. Case 2 stability analyses performed on the upstream slopes of Sections A and B are shown in Fig.12 and Fig.13.

Table 4 Factor of safety values from slope stability analyses

	Section A		Section B	
Case	U/S	D/S	U/S	D/S
Case 1	1.31	2.37	0.99	2.88
Case 2	1.48	2.37	1.15	2.88

Note: U/S = upstream, D/S = downstream

The results of the analyses performed also indicated that considering anisotropic behaviour in clay was a better representation of the dam as the numerical model was able to capture the observed behaviour on site. Proactive rehabilitation measures in this dam is on-going in order to address the slope instability.

5. CONCLUSION

Observations from site investigation and soil sampling indicated that the clay core, blanket and foundation of an aging water-retaining dam had fissured structures. The clay foundation fissuring was more intense than the clay in other locations

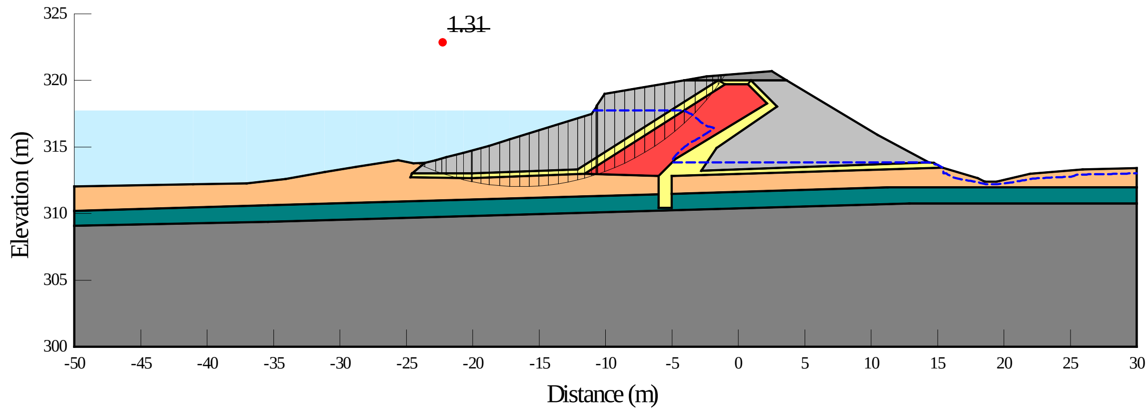

Fig.10 Slope stability analysis for Section A using Case 1.

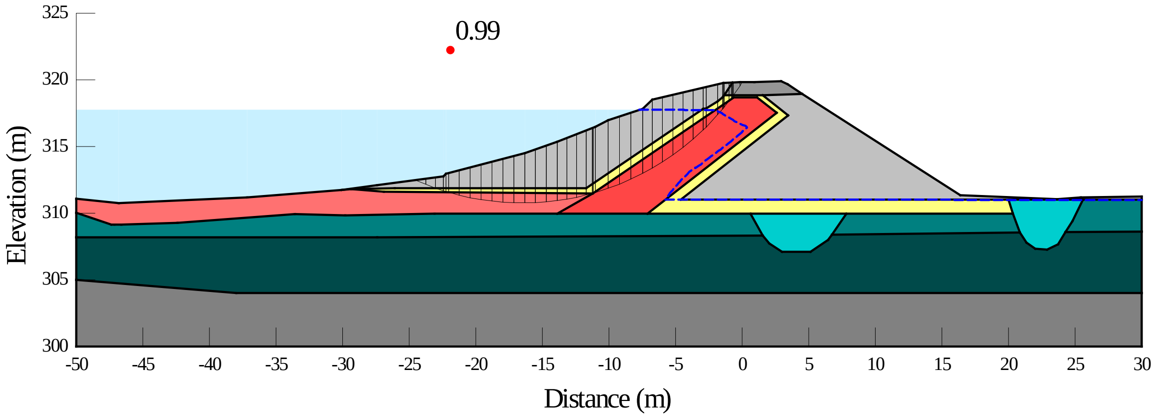

Fig.11 Slope stability analysis for Section B using Case 1.

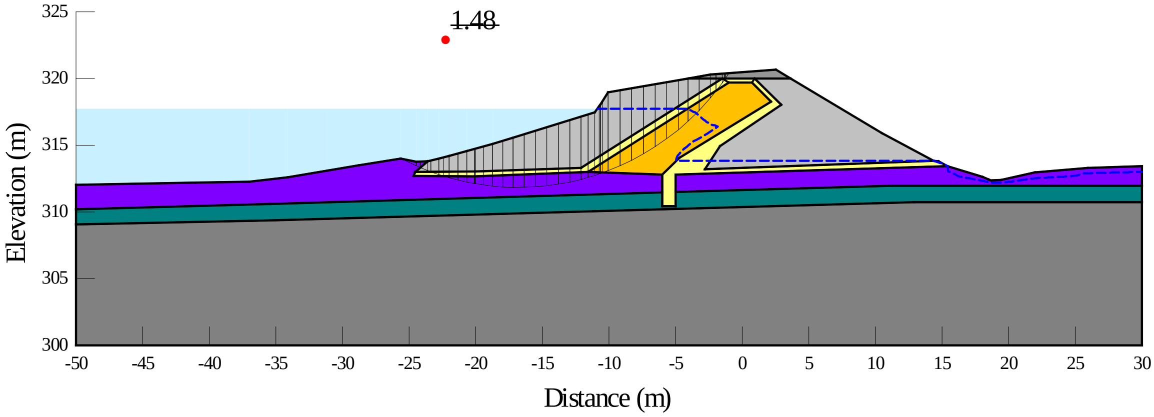

Fig.12 Slope stability analysis for Section A using Case 2.

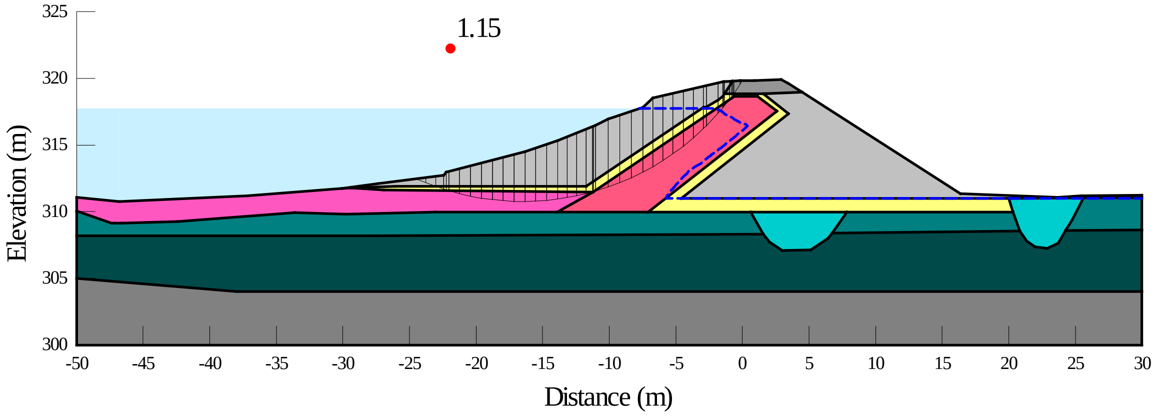

Fig.13 Slope stability analysis for Section B using Case 2.

and had more silt pockets. Despite the difference in the degree of fissuring, all tested samples were similar in terms of structural and mineralogical composition. The micro fabric of the clay was considered anisotropic from interlayered smectite and illite. The presence of silt could also influence the anisotropic behaviour of the clay foundation in general such as in terms of strength and permeability.

Experimental investigation indicated that other than anisotropy in its mineralogical composition, the undrained and drained strength of the materials used in construction of old earth fill dams were anisotropic. Strength anisotropy was evident in all tested clay as samples had 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. Intense fissuring of the clay foundation resulted to a bilinear failure envelope, while the clay core and clay blanket had a more uniform failure envelope.

The slope stability analysis considering strength anisotropy was a better representation of what was observed on site concerning the aging earth dam in this study. Based on site exploration, laboratory investigation, and numerical modeling analysis, the dam operator and owner are carrying out proactive measures in order to meet current dam safety standards.

6. ACKNOWLEDGEMENTS

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