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The Use of X-ray to Investigate Clay Shale Within a Landslide

Wallin, K.A., & Hendry, M.T.
Department of Civil and Environmental Engineering
University of Alberta, Edmonton, Alberta, Canada

ABSTRACT
X-ray computer tomography is a powerful non-destructive analysis tool used since the early 1970's to observe internal structures of objects based on variations in density and atomic composition. Initial CT applications occurred primarily within the medical industry. More recently, CT has gained popularity in the geoscience community due to greater availability and affordability of scanners, particularly medical grade and desktop scanners capable of micro CT imaging. Within the geosciences, however, CT remains under utilized as a core analysis tool for slope stability. This paper reviews potential geoscience applications of CT techniques, explores reasons for under-utilization of CT technology and assesses its overall validity as an analysis tool for slope stability purposes by presenting a case study of an active slow-moving landslide in the Assiniboine River Valley affecting Canadian National Railway's Mainline.

RÉSUMÉ
La tomographie par ordinateur aux rayons X est un puissant outil d'analyse non destructif utilisé depuis le début des années 1970 pour observer les structures internes des objets en fonction des variations de densité et de composition atomique. Les premières applications de tomodensitométrie se sont produites principalement dans l'industrie médicale. Plus récemment, la tomodensitométrie a gagné en popularité dans la communauté géoscientifique en raison de reduction de prix et de disponibilité des outils, en particulier des scanners de qualité médicale et de bureau capables d'imagerie micro-CT. Dans les géosciences, cependant, la tomodensitométrie reste sous-utilisée comme outil d'analyse de base pour la stabilité des pentes. Cet article passe en revue les applications géoscientifiques potentielles des techniques CT, explore les raisons de la sous-utilisation de la technologie CT et évalue sa validité globale en tant qu'outil d'analyse à des fins de stabilité des pentes en présentant une étude de cas d'un glissement de terrain actif dans la vallée de la rivière Assiniboine affectant la voie principale de Canadian National Railway.

1 INTRODUCTION

Slope stability is a critical terrain characteristic for safe railway operation and a focus of geotechnical engineers globally. Recent work by Porter et. al. (2019) examining impacts of landslides within the Western Canadian Sedimentary Basin (WCSB) that encompasses the Canadian Prairies, reveals that Canada's two major rail service providers incurred annual costs ranging from $10 to $18 million in direct costs from landslide damages and prevention efforts. Within the WCSB, the Assiniboine River Valley is one of the most critical rail transportation corridors connecting the east to the west in Canada.

All areas with higher relief located within the Canadian Prairies are susceptible to some level of landslide activity, including the Assiniboine River Valley. Valley walls downcutting into the underlying Cretaceous-aged bedrock deposits, coupled with other well-known phenomena like ice-thrusting and valley rebound, has created preferential planes of weakness vulnerable to failure at angles of less than 7 degrees (Ruel 2018). Canadian National Railways (CN) mainline, the Rivers Subdivision, travels through the Assiniboine River Valley over a 90 kilometer distance between Melville, Saskatchewan and St. Lazarre, Manitoba. Over this stretch, slope movements have been recorded at more than 22 locations, both as shallow rotational and deep-seated translational type movements.

In August 2019, a geotechnical investigation was completed at Mile 184.4 of the Rivers Subdivision within the slide mass of a slow-moving landslide affecting CN's Rivers subdivision near Miniota, Manitoba (Figure 1). A continuous core sampling technique was applied at the site where samples were collected directly into plastic liners for preservation purposes. Samples were then transported to University of Alberta facilities where they were scanned using a medical grade X-ray Computerized Tomography (CT) scanner to observe and log core sample features. Images generated were then further utilized to plan a laboratory testing program.

Based on an extensive literature review, whole-core CT scanning is an underutilized technique to explore slope instability within geotechnical studies. This paper presents a practical approach to assess instability of a slow moving deep-seated translational failure within an argillaceous deposit through an analysis of the Mile 184.4 site within the Rivers Subdivision. Multiple X-ray CT techniques are also examined and benefits and nuances of their utilization in relation to slope stability problems is discussed.

Figure 1. Site location.

2 BACKGROUND

Geological factors can have resounding effects on the engineering behavior of argillaceous deposits. Thomson and Morgenstern (1979) outline geological factors affecting highly overconsolidated shales and soft rocks within the Canadian Prairies, including depositional environment, lithology, stratigraphy, stress history, structure, climate, geomorphology and groundwater. Understanding geological site histories is a crucial step to determine variables driving kinematic movement of slopes and what geotechnical engineers may need to look for in the field to effectively assess sites.

The study area examined in this paper is located along the southeast corner of the WCSB (Figure 2). This area is generally underlain by Phanerozoic sedimentary rocks characterized by nearly horizontal bedrock covered by a thick mantle of glacial drift (Douglas et al. 1970). More locally, the area lies on the northeastern border of the Williston Basin, which is typically comprised of a thick blanket of Mesozoic and tertiary clastic rocks that overlie carbonates and evaporites of Paleozoic age (Douglas et al. 1970; Stott and Aitken 1993).

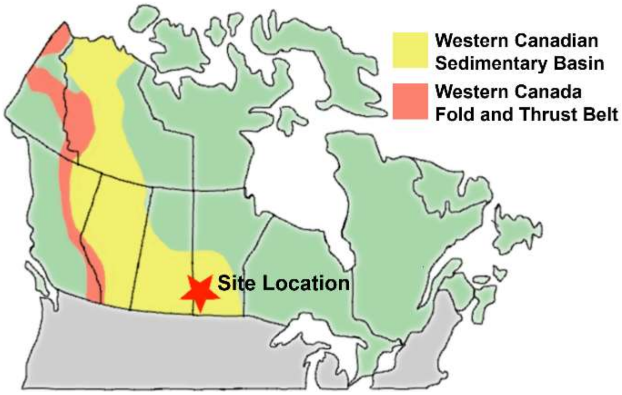

Figure 2. Western Canadian Sedimentary Basin (after Porter et al. 2019).

In the early Cretaceous period, the advance of the Beaufort Sea, which joined itself to the Gulf of Mexico, formed the epicontinental Western Interior Seaway (Yong 2003). During this time, extensive marine shale bedrock was deposited over the area occupied by the Seaway, including the southern portion of Manitoba. The shale bedrock at the site was deposited with near horizontal beds, with a minor inclination to the west due to its position on the near shore of the Williston Basin (Ruel 2018). Volcanic activities also occurred throughout the late Cretaceous period, namely from volcanic processes in southwestern Montanan and Idaho causing the presence of bentonite both as an admixture and as seams within the cretaceous deposits (Thomson and Morgenstern 1979; Yong 2003). Four glaciations then occurred in Canada during the Quaternary period. During these glaciations, extensive glacier ice-thrusting occurred throughout the Canadian Prairies (Sauer 1978; Porter et al. 2019), resulting in the deformation and shearing of underlying bedrock and glacial sediments, which in turn resulted in pre-sheared zones.

Formation of the modern-day Assiniboine River Valley occurred during the last of the four glacial retreats in the Pleistocene Period. The formation of the Valley occurred in several steps. The first consisted of the formation of the Assiniboine River as a major spillway and meltwater channel into glacial Lake Agassiz during the northerly ice retreat. The valley was then excavated to a depth between 15 m to 30 m above the modern Valley bottom during the continued northern ice retreat. A large drop in glacial Lake Agassiz then resulted in the Valley reaching its final glacial depth. A re-advance and retreat of an ice sheet in western Ontario created a variation in Lake Agassiz that deposited most of the alluvium sediments seen within the Valley today. The final formation step consisted of lateral erosion and slumping of Valley walls to create the undulating landforms seen today (Klassen 1972; Yong 2003).

Regional instability within the research area dates to the initial construction of the Rivers Subdivision. Reports from the early-1960s first detail movements observed within the Valley. Shallow slides tend to occur in the colluvium materials found near upper portions of Valley slopes and are commonly seen across the entire area. Deep-seated failures within the area are often observed to be slow moving and occurring along pre-sheared zones or weak bentonitic seams found within cretaceous-aged clay shale bedrock deposits. These deposits are commonly found to daylight along the Valley walls of the Assiniboine River.

A conservative estimate of 22 slope movement zones have been identified by CN over a 50 km span of the track located within the Valley. In the immediate vicinity of the Mile 184.4 site, five deep-seated translational failures have been observed over a span of about 13 km of track. The largest and most active zone identified to date is located 1.3 km to the west of the research site, with an affected area of over 120,000 m^2.

Initial track displacements at the research site were reported in April 2000. Hypothesizing that deflections could be part of a larger slide occurring 100 m west of the site, site monitoring was suggested by the consultant first investigating the movement. No additional movements were reported until 2016, at which point track subsidence was observed. Movement was attributed to higher than average rainfall during spring and summer 2016. Track lifting and maintenance was then typically required one to two times per year. In 2019, a site investigation was organized by CN and the University of Alberta through their collaborative Railway Ground Hazard Research Program (RGHRP).

3 SITE CHARACTERIZATION AND PROBLEM DEFINITION

Understanding and characterizing landslide features and history is critical to determine driving factors behind the movement. Identifying movement type, stratigraphic layers in which the movement is occurring, and known layer features help engineers make informed decisions of how to assess and analyze landslides. This section presents the initial site investigation. Findings of an X-ray CT analysis to characterize zones in which movement may be occurring are then presented.

3.1 Drilling Investigation

A drilling investigation was completed between June 3 and 7, 2019, with two boreholes advanced to depths of about 35 m. Boreholes were advanced using a continuous core sampling technique where a plastic liner was placed inside of an HQ3 triple tube core sampler. Samples were recovered directly into the liner, removed from the hole and sealed immediately on-site using a composite wax mixture of beeswax and paraffin. Due to time and budgetary constraints, sampling was only completed on one borehole. Following completion of boreholes, a slope inclinometer (SI) casing was installed to the termination depth and five vibrating wire piezometers were attached to the outside of the casing.

This sampling methodology limits the ability of field personnel to thoroughly identify lithology while on site; however, sample handling is minimized, as is disturbance and moisture loss. Lithology can then be thoroughly logged afterwards in a laboratory setting. X-ray scans of core samples were then taken through the plastic liners, which allowed for the relatively undisturbed samples to be non-destructively scanned and digitally recreated using CT whilst being preserved for additional laboratory testing. Core samples were scanned by InnoTech Alberta in Edmonton, Alberta.

A site reconnaissance was completed concurrently with the drilling investigation, with a preliminary outline of the failure extents defined and all visible site features logged. Figure 3 illustrates features observed during site reconnaissance, including an inactive scarp adjacent to the active movement zone and a toe scarp feature extending approximately 265 m parallel to the direction of the track. The extent of the movement zone appears to be bounded by two shallow drainage features with runoff/seepage zones found directly downslope in the valley bottom. The toe scarp feature was observed to be sliding overtop of the vegetation found down slope rather than having an upward rounding type movement. This is indicative of a translational failure type movement.

3.2 Local Geology

The general stratigraphy identified on site consisted of fill underlain by glacial till containing sand lenses and pockets further underlain by clay shale. Geological mapping work completed in the area by the Manitoba Geological Survey (MGS) reveals that the predominant bedrock member that outcrops along the eastern wall of the Assiniboine River Valley is the Cretaceous-aged Pierre Shale Formation. Formations of Cretaceous shales, including the Pierre Shale Formation, are typically interbedded with siltstone, sandstone, limestone and bentonite (Scott and Brooker 1966).

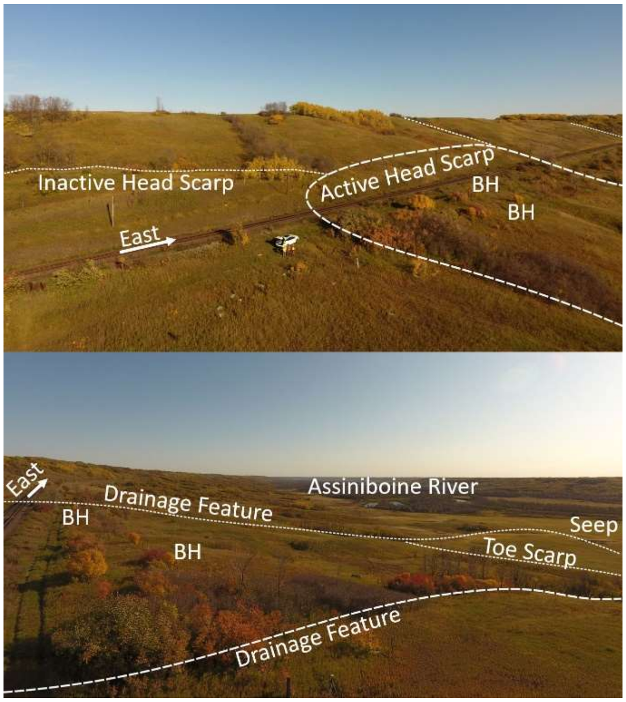

Figure 3. Mile 184.4 site features (courtesy of the Geological Survey of Canada).

Nearby investigations reported by Yong (2003) and Ruel (2018) support work completed by the MGS (Bamburak and Nicolas 2010; Matile and Keller 2012). This work indicates near surface bedrock found at the research site belongs to the Millwood Member of the Pierre Shale Formation. The Millwood member is an overconsolidated bentonitic clay shale composed of olive-grey silty clay with abundant clay-ironstone concretions (Bamburak and Nicolas 2010). Near-surface observations reveal a “popcorn-like” weathering pattern. According to Bannatyne (1970), the clay particles within the deposit primarily consist of kaolinite and partly swelling montmorillonite. The thickness of the Millwood Member typically increases from east to west. Thickness’ up to 150 m have been observed near St Lazarre, Manitoba, located approximately 50 km to the north of the research site.

3.3 Potential Movement Mechanisms

Shales can generally be separated into two categories: soil-like compaction shales (typically R0 to R1 based on the International Society of Rock Mechanics (ISRM) classification) and rock-like shales (typically R1 to R2 based on ISRM). In general, bedrock deposits in the Canadian Prairies, like the Millwood Member, are poorly indurated and often fall into the soil-like compaction shale category, more commonly referred to as 'soft rock'.

The laminated and interbedded nature of clay shales creates a behavioral anisotropy within these deposits. The anisotropy can further be attributed to factors including the preferential horizontal orientation of the long axis of clay particles during deposition and the stress history experienced by the deposit (Salager et al. 2013). The stress history of the Mile 184.4 research site includes up to four glaciations, which created an anisotropic loading condition on the material where the vertical overburden stresses were much greater than horizontal stresses. These factors contribute to an inherent anisotropic behavior (often considered cross-anisotropic) leading to localized failures along weaker zones like bentonitic layers or pre-sheared zones within the clay shale (Mollard 1977). Bentonite is particularly important to identify at the research site due to its high plasticity and low shear strength; as well as, due to reports of slope movements in the region along weak planes with residual shear strength values as low as 7 degrees, which indicates its presence (Ruel 2018).

Other factors occurring during the deposition of clay shales can create natural defects, including features like fissures and slickensides. Hsu and Nelson (1993) describe several of these mechanisms, including: formation of defect zones around concretions and other zones of stiffer materials during deposition and diagenetic processes; shear stresses and strains induced by glacial loading and unloading (including glacial thrust); and, defects caused by general erosion and stream down cut like differential rebound and swelling.

Brooker and Peck (1993) extensively researched clay shales located in western Canada, identifying four conditions leading to slope instability in the region, including: stratified materials with near horizontal bedding planes; bedding planes that exhibit lower than peak strengths; overconsolidation of clay shale from its depositional history; and, downcutting of valley walls which reduces the lateral pressure to zero.

Differential rebound is an important process to consider within all Canadian Prairie river valleys, as it has the potential to cause upwarping of the shale strata. Upwarping can lead to movements and slips along pre-existing weak planes like bentonitic layers, bedding planes and shear planes (Peterson 1958; Mollard 1977, Hsu and Nelson 1993). Upwarping can also lead to fissure development within a deposit. Skempton (1964) notes that as the number of fissures within clay deposits increase, there is a tendency for shear to occur at strengths closer to residual as opposed to peak, thus reducing the mechanical overconsolidation of the material (Picarreli et al. 2003). Observing these types of fissures using traditional geotechnical methods from samples obtained by standard drilling methods without disturbing or even destroying a sample is exceedingly difficult when dealing with clay shales.

There are two common types of strength weakening process that can occur in clay shale materials: progressive failure and delayed failure (strain softening). Clay shales in the Canadian Prairies are typically weak, brittle and sensitive to local strain concentrations. When plastic strain occurs in brittle materials, material strength decreases from peak, demonstrating a strain weakening behavior. If excessive movements occur, this strength can either reduce to a post-peak operational strength or to an ultimate strength known as residual.

Progressive failure occurs when the shear strengths of a brittle soil exhibiting strain weakening behavior are non-uniformly mobilized along a failure plane (Duncan et al. 2014). Reduction of lateral pressure to zero along valley slopes leads to a high horizontal to vertical stress ratio in the slope, where rupture surfaces can progress and reduce shearing resistance of the material until failure occurs and a new equilibrium is reached. These rupture surfaces often develop at the toe of excavations or down-cut valley slopes where stress concentrations are highest. The presence of bedding planes, pre-sheared zones and bentonitic layers can also cause them to occur anywhere along the valley slope. As rupture surfaces progress along the failure plane, peak material strength is never fully mobilized at all points. This suggests that once this process begin, the failure surface should never be assessed using peak strength; rather, a representative operational strength for the slope should be determined.

Delayed failure or strain softening tends to occur due to three main factors: strain weakening; an increase in moisture; and/or weathering (Brooker and Peck 1993). Based on tests of London Clay, Skempton (1977) demonstrates that peak strength softening can occur over time due simply to changes in water content. This results in reduced cohesion over time, decreasing the strength of the material from peak to fully-softened. Clay shales are sensitive to small increases in saturation, which can result in reduced strength and stiffness. The stress history of clay shales in the Canadian Prairies, coupled with their low-porosity, leads to these deposits being in a state of suction, thus making sample handling and preservation of utmost importance to integrity.

4 X-RAY COMPUTERIZED TOMOGRAPHY

X-ray CT is a non-destructive visualization tool where the internal structure of objects can be observed primarily through variations in density and atomic composition (Mees et al. 2003). Pioneering applications of CT images were largely qualitative and were used to identify dark areas within human lungs, indicative of diseases such as cancer. In recent years, increased availability of scanners and processing capabilities has led to the development of quantitative measurement methods (Thomson 2005). Within materials sciences, X-ray CT has been used in applications including three-dimensional density and porosity measurement, rock mechanics studies, failure plane and damage development during shear testing, correlation of core logs with well logs, characterization of drilling fluid invasion, fracture logging, aperture size analyses, soil-water-root processes, macroporosity assessments, core damage characterization, and to evaluate core flooding experiments (Wellington and Vinegar 1987; Hunt et al. 1988; Withjack 1988; Perret et al. 1997; Withjack et al. 2003; Cook et al. 2004; Walters et al. 1998; Thomson 2005; Liu et al. 2017). There are several CT scanning techniques that may be employed within geotechnical analyses, which will now be reviewed.

4.1 Whole Core Scanning

Whole core scanning consists of an X-ray CT scan of an entire section of core obtained from a test hole. Several scanning techniques have emerged since the creation of CT, including medical X-ray scanners, commercial, customized, and industrial benchtop scanners. An advantage of using medical X-ray scanners is that long core sections can be scanned in a short period of time (Vaz et al. 2014). However, as sample size diameter increases, image spatial resolution decreases, with an estimated maximum resolution of 600 μm by 600 μm x 1 mm (Mees et al. 2003).

A limitation of using whole core scanning is that layer thickness and X-ray attenuation contrast relative to noise levels present can impact the probability of detecting whether layers assumed to be planar and perpendicular to the axis of the core can be identified. However, noise levels can be reduced by averaging over the plane. This limitation is particularly important when attempting to detect thin layers of bentonite embedded in surrounding kaolinite.

Scan parameters for the Mile 184.4 site using a medical X-ray scanner are presented in Table 1. Using this data, a detectability versus thickness graph can be constructed, which indicates the probability of detection. A bentonite layer approximately 300 nm thick should be detectable using this technology; however, this is based on ideal circumstances. Nonuniformity within the sample being scanned can reduce sensitivity, increasing the detectable thickness. For slope stability assessment purposes, this detection limit is more than acceptable.

Table 1. Characteristics of tested soils

Parameter	Value
Voxel Dimension	0.351 mm
Image Noise	25 HU[1]
Area	7800 mm^2
Kaolinite-bentonite contrast	250 HU (0.25 g/cm^3)

[1]HU = Hounsfield Units (a unit of measurement used by medical scanners normalized to the attenuation of water)

4.2 Micro CT

A primary benefit of micro CT is its capability to generate three-dimensional high spatial resolution images showing density contrast between minerals and void spaces (Liu et al. 2018). The higher spatial resolutions of micro CT allow researchers to observe intra-aggregate porosity and pore particle interfaces, specifically in coarser materials like sandstones. In geosciences, micro CT has been increasingly utilized to characterize reservoir rocks to optimizing hydrocarbon extraction. Micro CT images can be used to model pore size distribution, hydraulic conductivity, connectivity and tortuosity, all of which help researchers reproduce in-situ like conditions during 2-phase and now 3-phase flow analyses (Haghi et al. 2019).

Micro CT technology has been successfully applied to study deformation or crack development in clay shale samples to further understand damage development as it pertains to the mechanical behavior (Liu et al 2018). Due to small particle size, however, the total porosity of clay cannot be assessed even using the highest spatial resolution micro CT scanners (Vaz et al. 2014).

Other limitations of micro CT technology exist which restrict its applicability to slope instability projects. Micro CT spatial resolutions are limited to coarser materials like sandstones. Secondly, small sample sizes required to obtain spatial resolutions for micro CT analyses limits its applicability as a tool for large scale engineering applications. As such, micro CT is not currently a viable tool for slope stability assessment at this or any site consisting of argillaceous deposits.

4.3 Dual Energy Scanning

Dual energy CT scanning is another technique that involves scanning the same location of a sample twice using high and low X-ray energies. This concept emerged in the 1980's when Wellington and Vinegar (1987) discovered it is possible to produce separate images proportional to bulk density and atomic number using varying X-ray energy interactions with matter. At low energy, the probability of photoelectric absorption increases with atomic number and decreases with increasing photon energy; at high energy the probability of Compton scattering becomes dominant and depends on the X-ray energy and the electron density (Siddiqui and Khamees 2004). By measuring the attenuation of X-ray beams at two different energies, the amount of Compton scattering and photoelectric absorption occurring within the material being traversed can be determined. Following this, it is then possible to calculate the effective atomic number and electron density of an object if enough energy separation is used (Saddiqui and Khamees 2004).

Scanning materials at two different energies results in a system of equations with six unknowns. A linearized approximation of these values can be determined by scanning three calibration samples of known density and atomic number. The calibration samples should be chosen such that density and atomic number are close and that their values 'surround' minerals of interest. An example is shown in Figure 4 where fused quartz, dolomite, and talc samples would be used to calibrate a clay shale sample expected to contain common types of clay (kaolinite, montmorillonite and illite).

Dual energy scanning has significant limitations in analyses of argillaceous soils due to atomic numbers of the three most common types of clay being relatively similar. This raises two main concerns, the first being that the primary difference between clay types are their crystalline structures, which dual energy scanning cannot observe. Secondly, clay is heterogeneous in nature. Clay mixture heterogeneity can create discrepancies in determining the exact type of clay present, especially when compared to denser materials like rock, reducing the effectiveness of repeated scans. Often, additional laboratory testing is still required to confirm the exact properties of a layer through a combination of X-ray diffraction analysis and/or Atterberg limits testing.

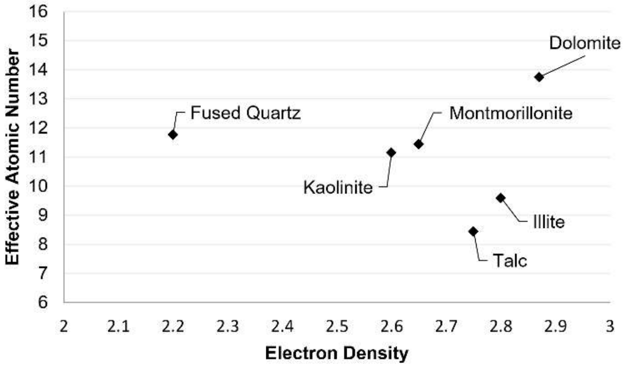

Figure 4. Example calibration materials for clay shale.

Although dual energy scanning provides insights into the effective atomic number and electron density of materials, additional costs of re-scanning core sections and increased data processing requirements offset benefits when compared to whole core scanning. Figure 5 illustrates four images generated from a dual energy scanning process. The whole core scans shown in a) and b) provide clearer insight into the layering present in the core run, whereas c) and d) simply indicate that the atomic number and bulk densities of the materials may be closer than expected when looking at the whole core scans.

Additionally, techniques have been developed to correlate greyscale or Hounsfield Units (HU) output by medical X-ray scanners to bulk densities for fine grained soils. Using these correlations and then identifying layers using greyscale images provides the engineer with similar information at a reduced cost and effort. Dual energy scanning may not provide enough additional value to be a viable slope stability assessment tool.

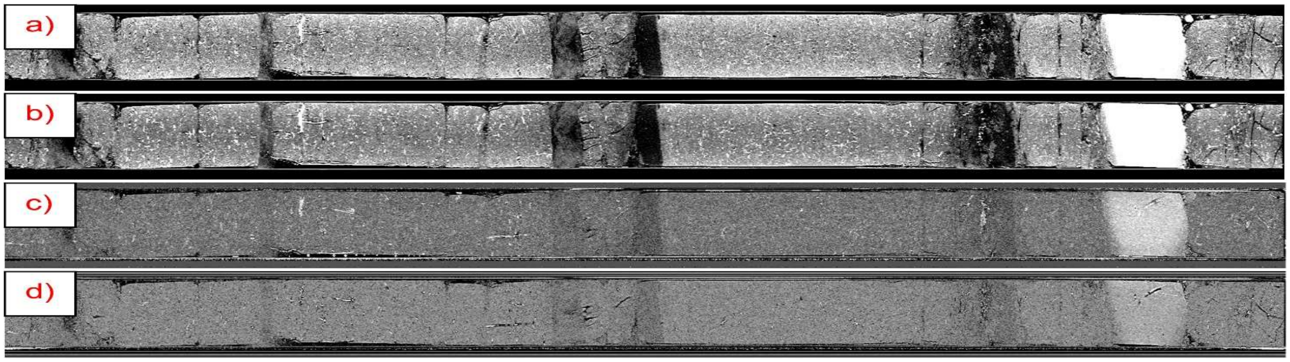

Figure 5. Example of Dual Energy scan images from Mile 184.4 Site: (a) low energy whole core scan, (b) high energy whole core scan, (c) reconstruction based on atomic number, and (d) reconstruction based on bulk density.

5 APPLICATION AND DISCUSSION

The drilling program completed at Mile 184.4 cost around $50,000 for sampling of one borehole and instrument installations in two boreholes. This total excludes any additional consulting costs and internal overhead costs typically incurred when organizing drilling programs. Therefore, $50,000 (a lower bound estimate) produced a total sample recovery of approximately 28 m when accounting for core loss. The cost of completing the whole core X-ray scans was $4,250 or $150/m. The engineer must now choose if this cost is warranted based on value added. To further illustrate the value of whole core CT, this section discusses work completed at Mile 184.4.

Whole core CT preserves drill core samples while providing insight into density profile and layering present making it particularly well-suited to the study of soft-sediment structures or materials requiring extensive preservation like clay shales. With 28 m of recovered core, determining which sections are of high priority and planning an appropriate laboratory testing program to accurately and effectively identify the properties of the soils or rocks is crucial. Typically, the engineer would choose a laboratory testing program based off the borehole log prepared by field staff and a visual examination of core samples. If these samples were placed into liners like the Mile 184.4 site, this visual examination would need to be completed through the liners or the liners would need to be removed. Opening the liners could lead to small changes in moisture content, which can lead to a decrease in the samples strength making it less representative of what is found in-situ. Completing X-ray scans of the core through the plastic liners allows sample integrity to be preserved while providing a visual of the macro properties present. This is extremely valuable for determining zones of interest along the borehole profile and for planning the laboratory testing program.

Analyzing microfabric and macrofabric structures of a clay provides valuable insight into their depositional and environmental history, chemical and physical weathering, and stress history (Holtz et al. 2011). In terms of slope instability, the microfabric provides more of a fundamental understanding of clay behavior and the macrofabric plays more of a role in determining the engineering behavior. Macro features often control the response of the entire soil mass to engineering loads. Thus, understanding them is important to characterizing whole slope behavior. Insight into the macrofabric features present in the core samples can be obtained using whole core CT, including features like joints, fissures, intermediate silt and sand seams, varves and other defects or inclusions that may influence the deposits behavior. Examples of macrostructures observed at the Mile 184.4 site are shown on Figure 6.

By examining the images obtained from whole core CT scanning, zones of interest can be effectively targeted for a laboratory testing program while avoiding non-essential zones, saving both time and money. CT images can also illustrate small fissures or zones where core samples may have been damaged during the sampling process. Mechanically damaged core samples are typically avoided when completing strength characterization tests (i.e. triaxial testing). An example of mechanically damaged core from the Mile 184.4 site is provided in Figure 7. Much of this core contains mechanical damage resembling that of core disking. Through whole core CT, this sample may still provide valuable characterization information, but would generally not be considered viable for strength testing.

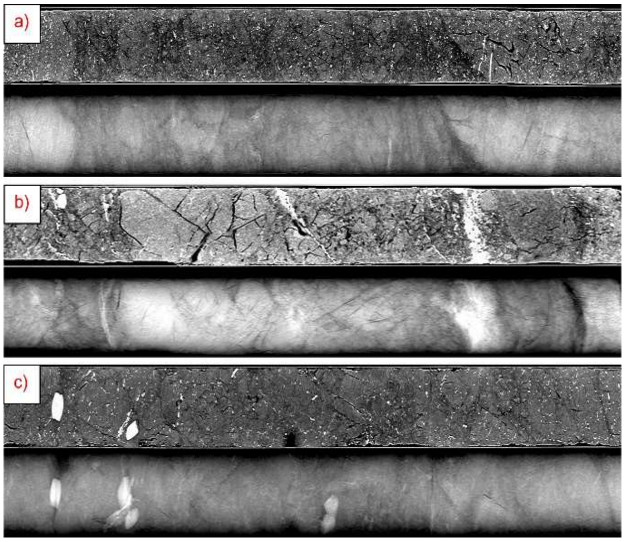

Figure 6. Examples of macrostructures observed from whole core X-ray CT single slice and volume renderings: (a) lower density layer, (b) sand lenses and high heterogeneity, and (c) dense inclusions of either sand of gravel.

Figure 7. Example of mechanically damaged core.

Having the cores preserved throughout the scanning process also affords the engineer time to observe slope movement development in the instrumentation installed at the site. Movement zones observed within the slope inclinometers can be targeted using whole core CT scanning to save on scanning costs. Figure 8 shows a preliminary assessment of a core sample found within the movement zone at Mile 184.4. A movement zone was noted at a depth of about 16 m below ground surface. The core run which correlated to this depth can then be examined. The core is relatively intact in the upper third. What appear to be natural fractures can be observed in the lower two thirds. If the engineer further examines the damaged section of the core and plots it against the correlated bulk density it can be observed that there appears to be three main zones, a weak layer with a lower bulk density than the surround materials (defined as the weak zone or WZ), a upper damaged zone (UDZ) above the WZ and a lower damaged zone (LDZ) below.

The UDZ appears more fractured than the LDZ, extending about 320 mm above the WZ. Fractures observed in the UDZ occur in intervals increasing from about 12 mm near the WZ to 70 mm moving up along the vertical core axis. The LDZ extends about 350 mm below the WZ. This zone appears to visually show signs of cracking/fractures; however, based on a review of the bulk density versus depth plot, there only appears to be two fractures, one approximately 100 mm below the WZ and another about 325 mm lower. Although there appear to be several fractures along the LDZ, based on the bulk density chart these features do not persist through the cross section of the core. This analysis could then indicate that the movement is generally occurring within and above the identified WZ.

A high-level qualitative analysis comparing bulk density versus water content of the core can also be completed. This is based on the interpretation that the darker bands on the scans have a lower density due to the material having a higher water content. Three assumptions are required for this: the material does not vary in composition along the core run (i.e. is homogeneous except for water content); a specific gravity of the material; and, that the material in-situ is under saturated conditions. Then applying the interpretation with phase relations, the average bulk density and correlated water contents can be determined as shown in Table 2. If considered viable, the WZ would then be assessed at a fully-softened strength as defined by Skempton (1977). As a caveat, the author/engineer still need to verify these assumptions and results with further laboratory testing of the core.

Table 2. Comparison of bulk density and water content

Zone	Average Bulk Density (kg/m^3)	Correlated Water Content (%)
UDZ/LDZ	2090	20.7
WZ	1890	33.7

If historical information is available, further correlations could be conducted using the Atterberg limits, including remolded shear strength values (Wroth and Wood 1978) or drained shear strength (Sorensen and Okkels 2013). However, these values would be highly speculative.

The above analysis is subjective and subject to change depending on which X-ray image is examined for analyse and how greyscale values are approximated. For this example, a free open-source software called ImageJ was used to re-slice the core scans and produce lengthwise cross-sectional slices of the scanned core sample.

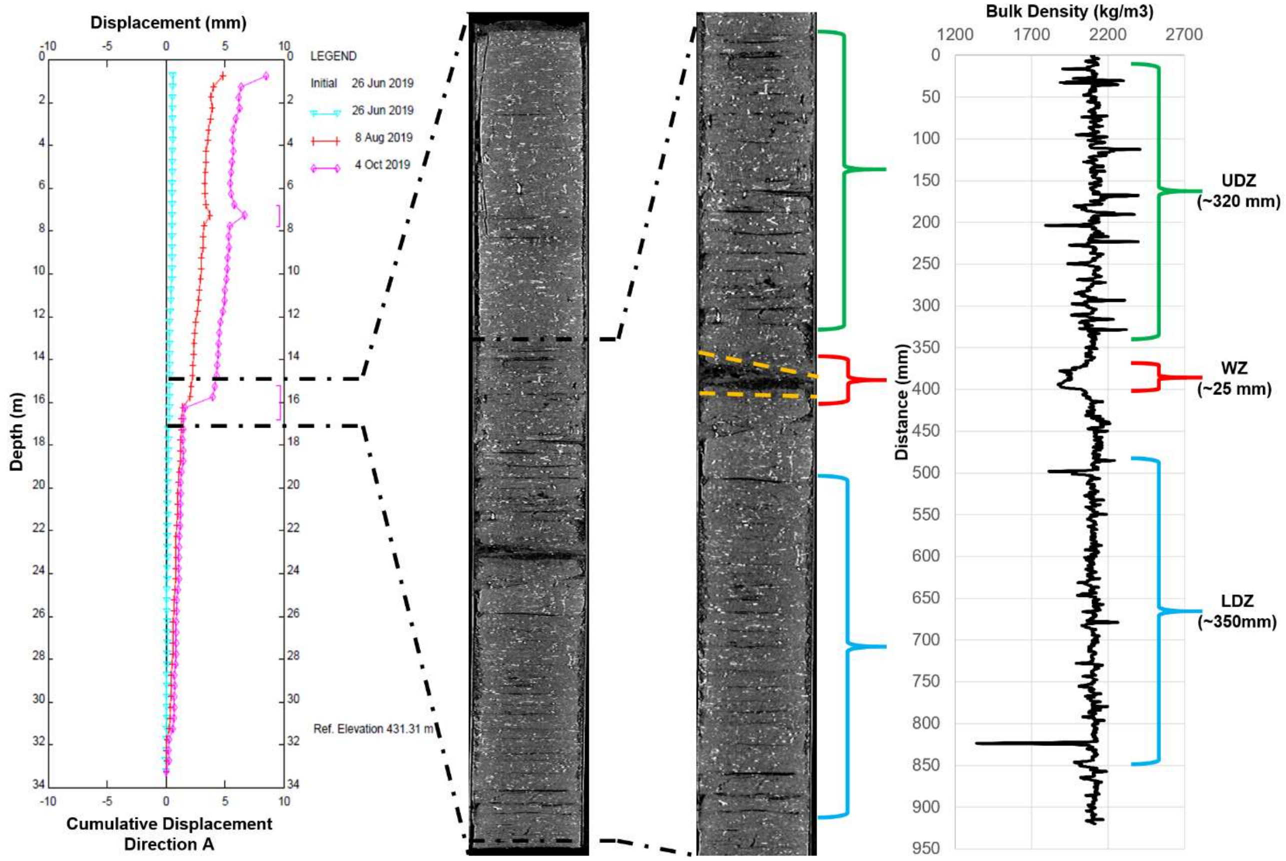

Figure 8. Example assessment of core section based on movement zone observed in slope inclinometer.

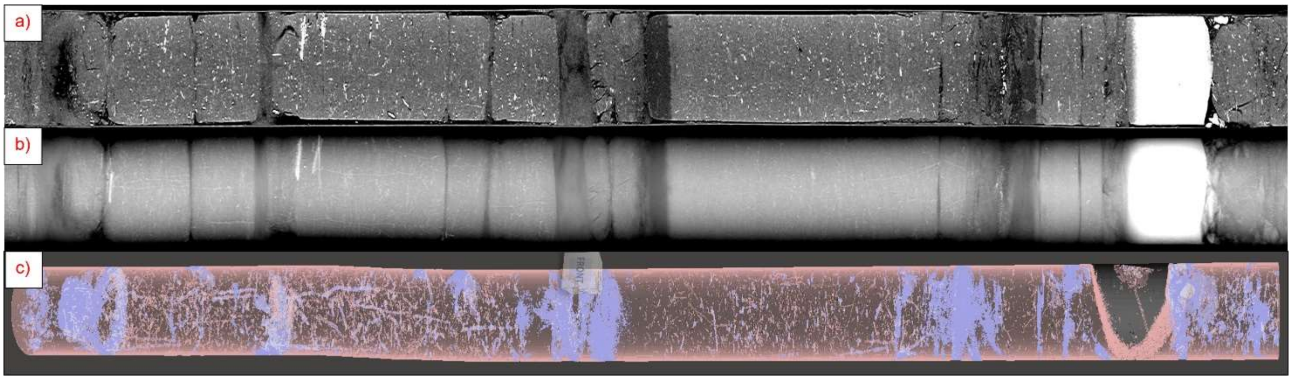

Figure 9. Example of 3D rendered core: (a) two-dimensional slice of core sample, (b) 3D volume rendering using ImageJ, and (c) 3D rendering using CTAN and MeshMixer of a fully meshed core run.

This technique produced a total of 273 slices, of which the 136th slice was chosen to analyze (as it roughly represents the center of the core sample). ImageJ then provides several methods to average the greyscale values. The chosen technique for this example was a box averaging, where the user draws a box over the section of interest and then the software provides an averaged plot of grayscale value versus distance. Information from this plot was then exported into Microsoft Excel and the Amos et al. (1996) correlation to relate grayscale values to bulk density for fined grained materials was applied.

This analysis can be completed in less than one hour and provides valuable information for slope stability assessment. The weak zone can now be targeted for further visual and laboratory analysis to determine its strength and characteristic values. This also indicates to the engineer that the slope movement observed at the site is likely along a thin weak plane. Having observed movements along this zone from the instrumentation on site, the engineer can then determine with relative confidence that the zone is likely at an operational strength below peak or even at residual strength.

Further analysis of other core sections along the borehole profile allows for other weak seams present within the deposit to be detected. This information can then be included in slope stability models for analysis, which can aid in confirming if any planned remedial designs will cause other weak zones to either reactivate or to begin moving.

Whole core scanning can also be used for quantitative analyses of internal features of geological materials (Mees et al 2003). CT allows for three-dimensional reconstruction of scanned samples, where selected features within the images can be segmented and/or analyzed. An example of a three-dimensional rendering is illustrated on Figure 9 above. Segmentation and meshing for the image were completed using commercially available software (CTAN) and three-dimensional image rendering was produced using open-source software (MeshMixer). Three sperate segmentations were applied to the core sample. The purple-blue color shows materials of lower grey-scale values or densities. The transparent red color shows intermediate density material which represents the primary matrix of the core sample. The solid grey color represents the high-density material located near the bottom of the core run. Three-dimensional imaging provides a striking visualization of core samples but does not provide significant added benefit in slope stability analysis projects when compared to two-dimensional grey-scale imaging and the added processing time and effort required. The core has, however, been fully meshed and could be analyzed further using Finite Difference or Finite Element Analysis software.

Nuances exists when it comes to quantitative analyses of clay. Clays are often deposited in ocean or lake settings and are thus typically composed of a mixture of sediments. This mixture of sediments can lead to limitations in the software's and user's ability to effectively segment and analyse images. As seen in Figure 9, although there are distinct zones of weaker and stronger materials, they do not always persist across the core. If not properly investigated this uncertainty could lead to speculation about their true engineering affects on the behavior of the deposit or slope.

Very powerful software, including Avizo, CTAN or PERGEOS, can be used to create interactive renderings that can be segmented and meshed for further analyses. The primary limitation of such software is their restrictive costs, which can exceed $40,000 per year plus annual maintenance fees. High-quality software can provide useful tools for many applications, specifically for hydrocarbon recovery optimization projects, but cost versus value added when assessing slope instability does not appear to be justified when compared to open-source software available freely online.

6 CONCLUSIONS

The increasing availability and affordability of X-ray CT devices enhances the ability of geotechnical engineers to characterize and understand dynamic processes in soil and rock. From a slope stability perspective, X-ray CT is a valuable tool to observe and analyze density variations and layering present within soil deposits. When coupled with continuous core sampling techniques like those employed at the Mile 184.4 site, X-ray CT provides an expedient and relatively inexpensive tool to visualize macro features within core samples.

More specifically, X-ray CT is useful in terms of providing two- and sometimes three-dimensional visualizations of core samples while preserving the mechanical integrity of samples. This affords more time to effectively plan laboratory testing programs. Use of X-ray CT is especially useful for analyses of soft-sediment structures or clay shales which can experience rapid degradations in sample quality if not properly preserved. Although other techniques and more advanced post imaging applications for CT images exist, cost restrictiveness offsets value added. In addition, free online software is more than capable of providing adequate images for the purposes discussed herein.

Based on available literature, this technique appears to be underutilized for characterizing core samples for slope instability projects. That X-ray CT has been infrequently used within geotechnical slope analyses may be a result of a lack of awareness that such technology exists, that the benefits of applying X-ray CT are not well known, a knowledge gap about the available open-source processing software, a misconception that image processing is difficult and time consuming, and an assumption that testing costs are too high. Using X-ray CT in a targeted manner can provide the engineer with great value, specifically for sites where clay shales are present. In these applications, X-ray CT is relatively inexpensive (~$150/m) when compared to other geotechnical testing approaches and provides significant advantages when assessing core samples in laboratory settings.

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