

THE GEOTECHNICS OF GLACIOLACUSTRINE SEDIMENTS AND ASSOCIATED LANDSLIDES NEAR ASHCROFT (BRITISH COLUMBIA) AND THE GRAND COULEE DAM (WASHINGTON)

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RÉSUMÉ

Les vallées Pléistocène dont les sédiments sont dominés par des dépôts glacio-lacustres sont monnaie courante dans le sud de la Colombie-Britannique et le nord de l'État de Washington. La stratigraphie de ces vallées comprend de multiples unités glacio-lacustres séparées par des tills glaciaires et des dépôts graveleux d'épandage, ceci reflétant de multiples épisodes de formation. Le compactage du aux glaciers ainsi que les glissements de terrain ayant survenu au cours des épisodes de déposition ont causé des surface pré-cisaillées, ce qui pourrait avoir compromis la solidité des sols en place. Dans cet article sera examiné les résultats d'essais sur des échantillons de sol de la région de Ashcroft et de Grand Coulee. L'aspect géotechnique de ces sédiments est examiné, en mettant l'emphase sur les relations entre les propriétés géotechniques et la résistance résiduelle de ces sols. Les paramètres contrôlant la résistance résiduelle sont examinés. Finalement, l'influence de l'épaisseur des varves et des pressions interstitielles sur l'état de contraintes effectives des pentes est examinée. La caractérisation précise de la résistance résiduelle est une composante essentielle à l'évaluation des risques de glissements de terrains dans ces matériaux.

ABSTRACT

Pleistocene valley fills dominated by glaciolacustrine sediments commonly occur in southern British Columbia and northern Washington. The fills contain multiple glaciolacustrine units separated by glacial tills and outwash gravels reflecting multiple episodes of formation. Glacial overriding and landsliding during deposition have caused pre-sheared surfaces in present day valley slopes which show evidence of being at residual strength. We review the results of soil tests on samples from the Ashcroft and Grand Coulee dam areas. The geotechnics of these sediments is examined with an emphasis on the relationship between geotechnical index properties and residual strength parameters. The controls on residual strength are examined. Finally, the influence of varve thickness and pore water pressure are related to the effective stress condition of the slope. The precise characterization of residual strength is a key component of landslide hazard assessment of slopes developed in these materials.

1. INTRODUCTION

Pleistocene valley fills dominated by glaciolacustrine sediments commonly occur in southern British Columbia and Northern Washington (Flint and Irwin, 1939; Milligan *et al.*, 1962; Evans, 1982; George, 1986). The landslide potential of these sediments has been realized and studied for some time (Stanton, 1898; Flint and Irwin, 1939). Due to the ever increasing development of the urban landscape and transportation networks in western North America the importance of defining and establishing awareness of this hazard has never been greater.

The fills contain multiple glaciolacustrine units separated by glacial tills and outwash gravels reflecting multiple episodes of glacial lake formation, glaciation onset and glacial retreat (Clague and Evans, 2003; Johnsen and Brennand, 2004). Typically the glaciolacustrine sediments consist of silt-dominated varves which contain thin layers of highly-plastic clay, as is the case in Thompson River Valley, British Columbia. Here the lower glaciolacustrine units have been overridden by glacial ice and show evidence of

glacial-induced deformation and shearing. In addition the sediments have been subject to contemporaneous landsliding during deposition and landsliding during valley-cutting periods between glacial episodes. Thus the glaciolacustrine materials in present day valley side slopes contain pre-sheared clay-smear surfaces which show evidence of being at residual strength (Clague and Evans, 2003). Figure 1, adapted from Milligan *et al.* (1962) illustrates the distribution of glacial lake sediments in Canada.

2. ARCHITECTURE OF VALLEY FILLS

The glacial history of a succession of valley fill sediments is perhaps the biggest control in determining its behaviour. This is evident in the Thompson River valley where surficial sediments have been formed during three glacial episodes, each separated by interglacial melt periods (Fulton, 1975).



Figure 1. Distribution of glacial lake sediments in Canada, adapted from Milligan *et al.* (1962), Figure 1.

The lowermost sediments include deposits from an early glacial advance (Early Pleistocene), which are composed of glacial till underlying interbedded glaciolacustrine silt and clay (Clague and Evans, 2003). The middle sediments were formed during a second glacial episode (approximately 40,000 years before present) and include sand and gravel till, glaciolacustrine silt and clay (Clague and Evans, 2003), and possibly other sediments deposited during the previous interglacial period (Fulton, 1975). The last group of sediments was deposited during the Fraser ice advance (10,500 to 20,000 years before present) (Fulton, 1975). It includes subunits composed of coarse gravel, sand, diamicton, silty till, and glaciolacustrine silt and clay. As a result of the complex glacial history surficial materials in the valley, which range in depth up to approximately 200 m, are nonuniform and spatially variable. Figure 2 illustrates the typical stratigraphic column from the Ashcroft area.

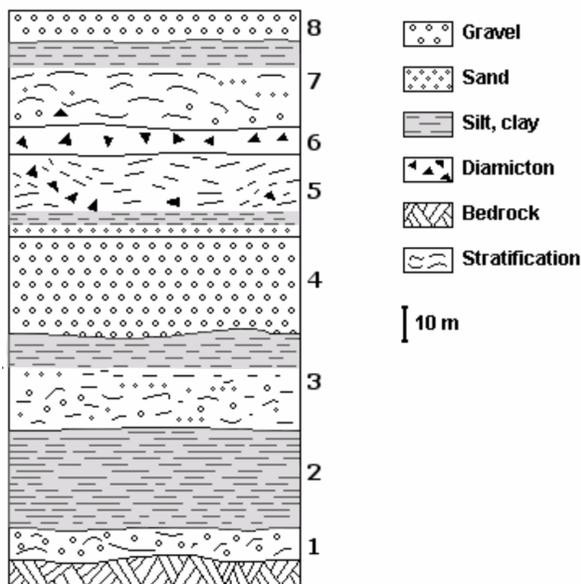


Figure 2. Typical stratigraphic sequence of valley fill sediment, adapted from Clague and Evans (2003).

The architecture of similar glacial deposits found in the Grand Coulee area is also complex (Figure 3). Flint and Irwin (1939) describe the glacial history of three groups of sediments, which were deposited during the Wisconsin (Fraser) glaciation. The lowest sequence is composed of massive silt, and varved silt and clay, deposited during oscillatory glacier damming, later followed by complete damming of the Columbia River downstream. As is the case in the Thompson River valley, these sediments have also been overridden by glacial ice and are distorted. A second sequence, mainly composed of glacial till and glaciofluvial gravels overlies the basal sequence. This marks the arrival of glacial ice in the Grand Coulee area. Late glacial valley fill deposits composed of lacustrine silt make up the upper portion of flat-topped terraces in the Columbia River valley.

One important feature of these valley fill sequences is the occurrence of varved glaciolacustrine silt and clay (Figure 4). These materials do not occur in all valley fills. Generally, it is these materials that control the landslide behaviour of valley side slopes due to their lower shear strength (Porter *et al.*, 2004). The engineering response to these soils is related to the nature of their deposition, which depends on their distance from the glacial front during time of deposition, size of the lake basin, proximity to inflowing glacial streams, and historical mass movement (Evans, 1982). They usually exist as alternating dark and light bands, with light bands being of higher average grain size (typically silt), and dark bands being of lower average grain size (typically clay), although it should be noted that a gradual transition of grain size does occur (Milligan *et al.*, 1962; Quigley, 1980). The alternating dark and light banded appearance of these sediments indicates that they were deposited in an annual winter-summer cycle, as described by Eden (1955). Coarser material (silt) was deposited during the summer months when glacial melting contributed to increased energy to glacial streams. During the winter months, when glacial melting was lower, finer-grained material (clay) was deposited (Eden, 1955). Varved sequences may be either silt-varve dominated or clay-varve dominated, indicating the dominant grain size in terms of relative thicknesses of silt or clay for a given succession (Evans, 1982). The thickness of each unit is not typically regular and varies within the stratigraphic column.

3. GEOTECHNICAL PROPERTIES

We tested the geotechnical properties of 41 soil samples collected from the silt and clay deposits of the Thompson River Valley, near Ashcroft, British Columbia. Of these, 16 samples were sent to the University of Warwick soils lab for ring shear and geotechnical index property testing. Through this testing it was possible to establish accurate index properties and residual shear strength estimates of the glaciolacustrine varved silt and clay of the Ashcroft area. A summary of the geotechnical data obtained in this study is provided in Table 1.

Table 1. Summary of the geotechnical properties of Ashcroft silt and clay.

Sample	Field Description	Liquid Limit %	Plastic Limit %	Plasticity Index %	Clay Fraction %	Ring Shear	
						Cohesion kN/m ²	Residual Strength °
Goddard Slide							
17AU-1A	Clay varve	84	24	60	34	-	-
17AU-1B	Clay varve	72	34	38	75	-	-
17AU-1D	Clay rich slickenside	76	32	44	59	-	-
17AU-1E	Clay rich slickenside	53	24	29	41	-	-
17AU-1F	Clay rich slickenside	81	33	48	34	0	33
17AU-1F	Clay rich slickenside	42	22	20	17	-	-
17AU-1G	Silt block	40	33	7	20	-	-
17AU-1H	Silt block	37	20	17	21	-	-
17AU-1I	Silt block	41	21	20	-	-	-
17AU-1L	Silt block	76	31	45	46	-	-
17AU-1L	Silt block	47	22	25	24	10	26
17AU-1M	Clay from shear zone	79	36	43	33	-	-
17AU-1N	Shear-zone clay block	58	25	33	31	-	-
17AU-1O	Clay	56	24	32	47	-	-
17AU-1O	Clay (for x-ray analysis)	66	28	38	-	3	15
North Slide							
17AU-2A	Clay	85	21	64	43	-	-
17AU-2B	Silt	38	26	12	17	-	-
17AU-2C	Silt	40	33	7	8	-	-
17AU-2D	Clay	80	37	43	45	-	-
South Slide							
17AU-3A	Clay	78	35	43	30	-	-
17AU-3B	Silt	37	24	13	11	-	-
17AU-3C	Silt	38	25	13	10	-	-
Ashcroft (CN 53.4) Slide							
18AU-1A	Silt block	39	23	16	27	-	-
18AU-1B	Silt block	36	24	12	2	-	-
18AU-1C	Silt block	34	25	9	13	-	-
18AU-1D	Silt block	41	24	17	20	-	-
18AU-1E	Clay	53	24	29	61	-	-
18AU-1F	Silt block	38	24	14	-	0	29
Mile 54 Slide							
18AU-2B	Clay	85	39	46	-	0	10
18AU-3B	Silt block	35	22	13	12	0	32
18AU-3E	Clay	63	35	28	-	0	11
1905 Spences Bridge Slide							
18AU-4A	Clay block (with silt?)	49	23	26	-	15	24
18AU-4C	Clay block (with silt?)	45	22	23	-	0	25

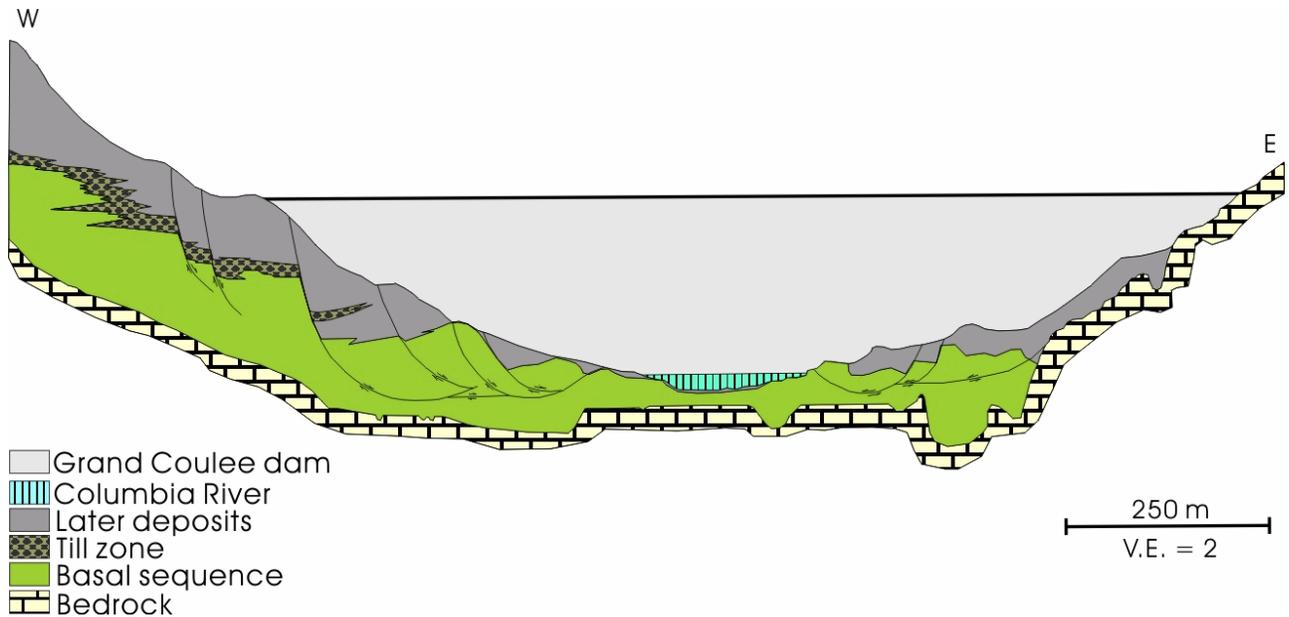


Figure 3. Cross-section of the surficial geology of the Grand Coulee dam site, adapted from Plate 1 in Flint and Irwin (1939).



Figure 4. Photographs of undisturbed varved silt and clay (above), and disturbed silt and clay (below), Thompson River valley, near Ashcroft, British Columbia.

Within the varved formations the silt bands are thickest compared to the clay seams, with a ratio of silt to clay thicknesses of approximately five to one, although this may vary. It is therefore possible to separate their constitutive components in order to determine their individual geotechnical properties. However, this is difficult to accomplish in practice since the clay seams in the Ashcroft glaciolacustrine silt and clay are very thin, and obtaining a representative sample is difficult. Each of the samples was described in the field to provide an indication of the silt or clay content. Additionally, the clay fraction of most samples was determined in the laboratory so that individual properties of clay and silt could be further distinguished. After laboratory analysis it was determined that only three of the clay varve samples had a clay fraction of greater than 50%. Wide ranges in index property values were observed for all data from the Ashcroft area. Plasticity indices range from 7% to 64%, and clay fractions ranged from 2% to 75%.

Residual shear testing was completed for 9 of the Ashcroft samples using a Bromhead ring shear apparatus at the University of Warwick soils laboratory. Results of this testing show a bimodal population of residual shear strength values indicating a sharp contrast in the residual strengths of the silts and clays. The lower population of residual shear strength values (clays) was found to be between 10° and 15° , and the upper population of values ranged from 24° to 33° . The bimodal distribution of shear strength values becomes more apparent when results of testing of similar materials found in the Grand Coulee area are included in the analysis.

Geotechnical testing of the Grand Coulee varved silt and clay was completed as a part of a riverbank stabilization study undertaken by the United States Bureau of Reclamation (Miedema et al., 1981; USBR, 1983). This

study was initiated when a large historic landslide reactivated within a populated area adjacent to the Grand Coulee dam following a sudden dam-controlled water level fluctuation in the Columbia River on June 4, 1978 (Miedema *et al.*, 1981). A six mile reach of the Columbia River Valley downstream of the Grand Coulee dam was studied to identify possible slope stability issues. This study has provided invaluable information regarding the behaviour of varved glaciolacustrine soils. The majority of samples tested had a clay fraction of over 50%. Residual shear strength of the clay ranged between 7° and 14°.

Figure 5 and Figure 6 show the combined results of index property testing and residual shear strength testing for varved silt and clay from both study areas. Figure 6 illustrates the aforementioned bimodal distribution of residual shear strength values found within the silt and clay formation, where the silt component has a higher overall residual strength compared to the clay component.

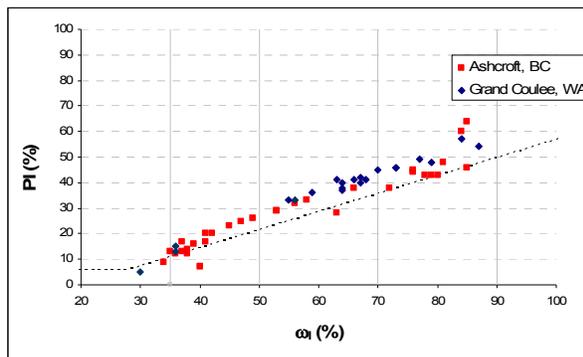


Figure 5. Plasticity chart of glaciolacustrine silt and clay near Ashcroft, British Columbia and Grand Coulee, Washington.

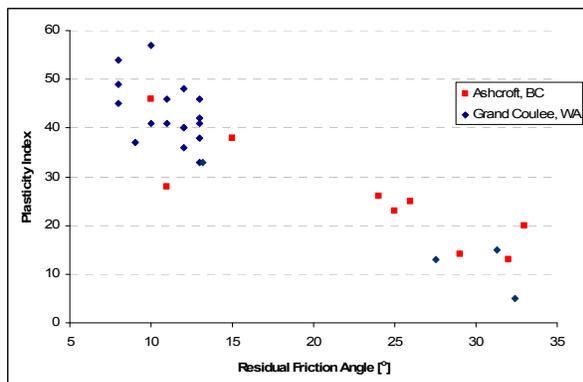


Figure 6. Plasticity index-residual shear strength relationship for glaciolacustrine silt and clay from the Ashcroft (BC) and Grand Coulee (WA) areas.

4. LANDSLIDES

Landslides commonly occur in valley fill sediments that contain some component of highly plastic glaciolacustrine material. A total of 13 major landslides are found on both sides of Thompson River Valley within a 10 km reach of the river south of Ashcroft (Porter *et al.*, 2002; Clague and Evans, 2003; Eshraghian *et al.*, 2006). These landslides have resulted in derailments and traffic disruption along the Canadian Pacific (CP) and Canadian National (CN) rail lines traversing the valley bottom since the construction of the rail lines over one hundred years ago (Stanton, 1898).

Hundreds of landslides have been identified within the Columbia River Valley in northeast Washington (Jones *et al.*, 1961). Some of these have resulted in the loss of infrastructure and some continue to threaten local slope stability. Glaciolacustrine silt and clay is responsible for those historical and recent landslides found in the vicinity of the Grand Coulee dam, which were (re)activated during the filling of the dam's reservoir (Jones *et al.*, 1961).

One important similarity between the Ashcroft and Grand Coulee landslides is that they are both occurring along pre-sheared surfaces caused by glacial overriding. This can reduce the strength of the material to residual values thereby preconditioning slopes to failure. The glacial history of valley fill material is therefore an important consideration when considering its design parameters.

These landslides commonly exhibit three failure mechanisms. Clague and Evans (2003) describe these failures. The first type is described as a slow moving rotational failure where large back-tilted blocks of sediment are preserved. The second type includes slow moving translational slides with little rotation. Eshraghian (2007b) gives movement rates of 2-10 cm/year for the slow moving failure mechanisms. The third type includes sudden rapid flowslides where the slide material is disaggregated while it flows along a gentle slope. Most landslides exhibit different combinations of these failure mechanisms. In all cases the slide surface is initiated along a weak plane (clay) within the glaciolacustrine sequence.

5. SLOPE STABILITY ANALYSIS

With the geotechnical controls on these landslides firmly established other reasons for slope failure can now be investigated. Although there are many possible controls on slope failure in valley fills (Porter *et al.*, 2004), the two discussed herein relate to varve thickness, and pore water pressure condition. In order to compare these two controls a basic slope stability analysis was performed using SLOPE/W, a slope stability analysis software package (GEO-SLOPE International, 2007). A slope was created that took the general slope geometry of the pre-1982 landslide that occurred south of Ashcroft (EBA, 1983). Varves having a thickness ratio of 5:1 were created within the slope to represent the different clay and silt bands within the glaciolacustrine sediment. Silt bands were defined as having a residual strength of 29 degrees and clay bands

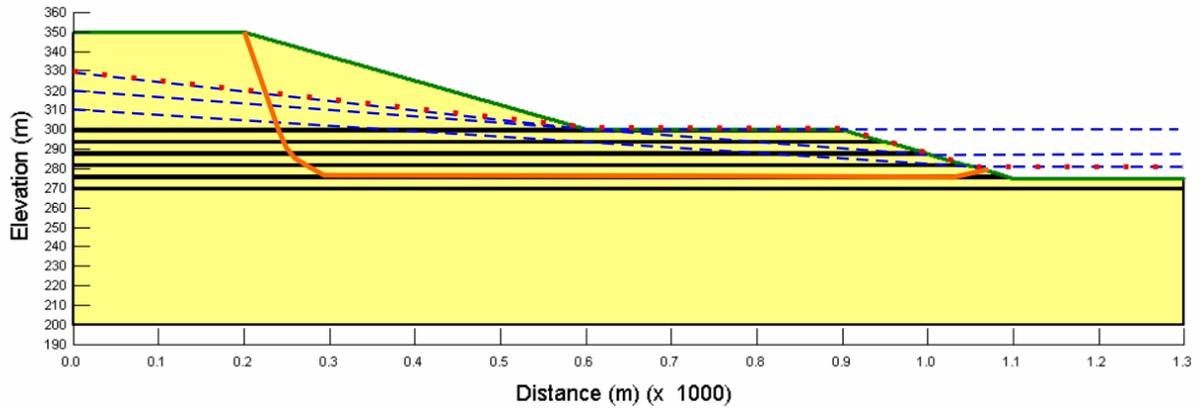


Figure 7. Model slope with four pore water pressure conditions used in the SLOPE/W stability analysis. In the figure scenarios 1 to 3 are the dashed lines, increasing upwards with 1 being the lowest, and scenario 4 is the dotted line.

were defined as having a residual strength of 9 degrees. Both materials were assumed to be subjected to glacial overriding, reducing any cohesion to zero. It should be noted that due to constraints on model resolution the model-scale varves are much thicker than in the real world case.

Four potential water table conditions were defined in the model by drawing simple phreatic surfaces. Artesian groundwater conditions, such as those shown in Figure 7, are expected based on the author's groundwater model of the Thompson River Valley, currently in progress. Hydrostatic loading at the toe of the landslide was neglected because it was assumed that the failure surface daylighted above any surface water body. Several potential failure surfaces were defined where failure occurs horizontally along planes of weakness (i.e. clay seams) then extends upwards by cutting steeply across alternating bands of sediment. These types of failure surfaces are common to the Ashcroft area (Eshraghian *et al.*, 2007a) A total of 8 analyses were completed: one for each of the four water table conditions in a silt-varve dominated scenario, and one for each of the four water table conditions in a clay-varve dominated scenario. Using the Morgenstern-Price method for each scenario, factors of safety of the slopes were calculated and used as a comparison between cases. The failure surface geometry was specified and identical for each scenario. Figure 7 shows the different pore water pressure conditions used in the analysis.

The factors of safety calculated using SLOPE/W for each simulation, are presented in Table 2. These results show that the silt-varve dominated slope yields a factor of safety that is approximately 20% greater than the clay-varve dominated slope for all pore water scenarios, indicating that silt-varve dominated slope will be less prone to failure than a clay-varve dominated slope.

As an additional means of comparison, the effective stress was calculated along the base of the failure surface and compared to the shear strength at the

same location. Figure 8 shows the resulting field failure envelope based on the 8 analyses of the model slope. As would be expected, all effective stress states are found between the failure envelopes for the silt and clay. The data lies closer to the clay failure envelope suggesting that the presence of clay plays a greater role in controlling failure than the silt component of mixed glaciolacustrine materials, regardless of the relative dominance of either silt or clay varves. This is likely attributed to the fact that the horizontal component of the failure surface is occurring along the weakest layer (clay) regardless of the thickness of that unit.

Table 2. Factor of safety calculations.

Pore water Scenario	Factor of Safety	
	Silt-varve Dominated	Clay-varve Dominated
1	1.72	1.41
2	1.52	1.21
3	1.47	1.16
4	1.33	1.04

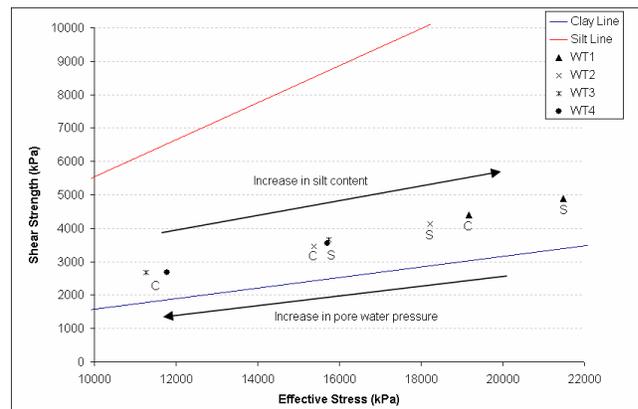


Figure 8. Field failure envelope of residual strength based on slope stability analysis of model slope in Fig. 7. All failure envelopes can be extended back to the origin (i.e., $c = 0$). WT = water table condition; S = silt-varve dominated; C = clay-varve dominated.

6. IMPLICATIONS FOR HAZARD MANAGEMENT

Valley fill deposits commonly found in western Canada and the United States are typically composed of a wide variety of materials in a single succession reflecting variability in the nature of their depositional environment. The occurrence of varved glaciolacustrine silt and clay within valley fill deposits is important with respect to local slope stability, urban development and infrastructure management considerations. Because these materials were formed in a glacial environment they may have been subjected to past glacial overriding, which may reduce their strength to residual values. An understanding of the glacial history of these materials is therefore required to appreciate their in situ behaviour. The relative abundance of clay and silt within the succession is an additional consideration. Using variable pore water pressure conditions basic slope stability analysis has shown that a deposit having a clay to silt thickness ratio of 5 to 1 results in a 20% reduction in the factor of safety when compared to a slope having the inverse proportions of clay and silt. Regardless of the relative thicknesses, the horizontal component of the failure surface will occur along the weaker layers (clay) of the formation.

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