Coefficient of consolidation of soils from the Mackenzie valley, Canada

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ABSTRACT
The paper presents values of coefficient of consolidation, C_v, of typical moraine sediments from the Mackenzie valley, NWT, Canada. Coefficient of consolidation is a key parameter for analysis of excess pore pressure and thaw consolidation settlement of fine grained soils in permafrost regions. Due to limited availability of tested values of this parameter, selection of C_v values for analysis of pore pressure and settlement during thawing and post thaw conditions is a difficult task for researchers and practitioners. In this paper, 20 soil samples from 8 landslide sites in the Mackenzie valley were collected and tested for coefficient of consolidation. The tested C_v values with other geotechnical index properties are presented to enrich crucial data for fine grained soils in the region.

RÉSUMÉ
Cet article présente des valeurs de coefficient de consolidation, Cv, de sédiments typiques d'une moraine provenant de la vallée du Mackenzie, NWT, Canada. Le coefficient de consolidation est un paramètre important dans l'analyse de pressions interstitielles en excès et de tassements de consolidation dus au dégel dans des sols fins de régions ayant du pergélisol. En raison de la faible disponibilité de valeurs testées pour ce paramètre, la sélection d'un Cv approprié dans l'analyse de pressions interstitielles et de tassements pendant et après le dégel est une tâche ardue pour les scientifiques et les ingénieurs. Dans cet article, 20 échantillons de sol provenant de 8 glissements de terrain de la vallée du Mackenzie ont été prélevés et testés afin de déterminer le coefficient de consolidation. Les valeurs testés de Cv ainsi que d'autres paramètres géotechniques sont présentés afin d'enrichir les données cruciales pour les sols fins de cette région.

1 INTRODUCTION

Soils subject to freeze-thaw effect in cold regions behave differently from those in temperate environment. Understanding consolidation behaviour of thawing soils is a challenging task for geotechnical practitioners and researchers. Morgenstern and Nixon (1971) developed a one-dimensional consolidation theory for thawing soils. It was formulated in terms of theories of heat conduction and of linear consolidation of a compressible soil. The theory assumes a moving boundary at the thawing front where excess pore pressure is generated from the pore water expelled during thawing. The following closed form solution was derived to calculate the excess pore water pressure (Morgenstern and Nixon 1971):

$$u(x,t)=\frac{P_0}{erf(R)+\frac{e^{-R^2}}{\sqrt{\pi}R}}erf\left(\frac{x}{2\sqrt{c_v t}}\right)+\frac{\gamma' x}{1+\frac{1}{2R^2}} \quad [1]$$

$$R=\frac{\alpha}{2\sqrt{C_v}} \quad [2]$$

$$\alpha=\frac{X}{\sqrt{t}} \quad [3]$$

Where notation, u is excess pore pressure; x, thaw depth; t, duration; P_o, overburden pressure; γ', submerged unit weight of soil; R, thaw consolidation ratio; α, thermal constant; C_v, coefficient of consolidation; and erf() error function.

Excess pore pressure during thawing can be a major cause of instability of ice-rich permafrost slopes. During thawing, shear strength reduces due to generated excess pore pressure which causes instability and movement of slopes (McRoberts and Morgenstern 1974). Excess pore pressure generated during thawing is governed by a key parameter: the thaw consolidation ratio, R. The thaw consolidation ratio depends on thermal coefficient, α, and coefficient of consolidation, C_v, of thawing soils (Morgenstern and Nixon 1971). McRoberts and Morgenstern (1974) indicated that the thermal coefficient is less influential to thaw consolidation as compared to the consolidation property of the thawing soil. Normally, the thermal coefficient, α, ranges from 0.01 to 0.1 cm/sec$^{1/2}$ as noted by McRoberts (1972). However, typical C_v values vary in the order of 10^{-1} to 10^{-5} cm^2/sec for sandy to clayey soils (McRoberts and Morgenstern 1974). Therefore, certainty of the thaw consolidation ratio largely depends on selection of appropriate C_v values. Despite its importance, little information is available about this parameter.

A list of available coefficient of consolidation data for soils from cold regions are compiled in Table 1. McRobert and Morgenstern (1973) indicated that the only Mackenzie valley soil for which C_v was known at the time was Mountain River Blue Clay. Some further studies have been done to determine C_v values of the soils in the Mackenzie valley and other cold regions (Morgenstern and Smith 1973; Nixon 1973; McRoberts and Morgenstern 1974; Nixon and Morgenstern 1974; Morgenstern and Nixon 1975; McRoberts and Nixon 1977; Roggensack 1977; McRoberts et al. 1978; Hanna and McRoberts 1988; Pufahl and Morgenstern 1979; and Ryden 1985). The data summarized in Table 1 presents previously assumed, derived and tested values of C_v in the above mentioned literature for pore water pressure, thaw settlement and slope stability studies. It can be seen that the majority of the available C_v values in Table 1 are assumed or derived (#1 to 6). Compared to abundant C_v data available for various types of soils in temperate regions, much effort is needed to enrich such information for soils from the permafrost regions. This is the main intention of this paper.

A testing program to determine a range of coefficients of consolidation of typical soils from the Mackenzie valley was carried out. A total of eight active landslide sites in the Mackenzie valley were selected for the study. Soils sampled from the selected locations were tested for C_v. The descriptions of the tested samples with geotechnical index properties, geographical locations and their coefficient of consolidation are presented.

Table 1. Some values of coefficient of consolidation from the literature.

#	Coefficient of Consolidation C_v, (cm²/sec)	Method of Acquisition	Soil and Other Information	Source
1	$5.0x10^{-4}$	Assumed	Mackenzie valley silty clay soil, recommended average value for the region	McRoberts & Morgenstern (1973)
2	$1.5x10^{-3}$	Assumed	Fort Norman silt, void ratio 0.85 and water content (W/C) 31%	McRoberts & Morgenstern (1974)
3	$1.0x10^{-2}$ to $5.0x10^{-2}$ $>5.0x10^{-4}$	Assumed	Sandy silt to silty clay for active layer; Below active layer (Mackenzie valley)	Pufahl & Morgenstern (1979)
4	$9.0x10^{-4}$ to $1.5x10^{-3}$ $1.5x10^{-3}$ to $4.0x10^{-3}$	Derived	For Sans Sault and Martin River silty clay and silt soil	McRoberts et al. (1978)
5	$1.03x10^{-2}$	Derived	Used for prediction of thawing settlement of hot gas pipeline in clayey silt foundation, Inuvik, NWT	Morgenstern & Nixon (1975)
6	$2.0x10^{-7}$ to $8.0x10^{-7}$	Derived	Sulphide-rich silty clay in Sweden; bulk density 1.4 kN/m³, saturation 93% to 104%	Ryden (1985)
7	$2.5x10^{-4}$ to $17.0x10^{-4}$	Tested	Remoulded Athabasca clay	Morgenstern & Smith (1973)
8	$1.1x10^{-2}$	Tested	Tested clayey silt sample, Inuvik, NWT: W/C 40%	Nixon (1973)
9	$3.4x10^{-3}$ to $26.7x10^{-3}$ $1.9x10^{-3}$ to $7.6x10^{-3}$ $6.1x10^{-4}$ $5.3x10^{-3}$	Tested	Undisturbed sample Norman Wells silt: W/C 36% to 50% Noell Lake Clay: W/C 33% to 79%; Remoulded Mountain River Clay: W/C 80%; Devon silt: W/C 50%	Nixon & Morgenstern (1974)
10	$2.3x10^{-2}$ to $7.1x10^{-4}$ $1.3x10^{-2}$ to $2.2x10^{-4}$ $1.6x10^{-1}$ to $5.8x10^{-5}$	Tested	3 sandy silt to silty clay soils, 35 km east of Fort Simpson: W/C 28.6% to 62.8% Landslide scrap at Norman Wells: W/C 24.5% to 51.2% 27 km north of Inuvik (Noell Lake): W/C 21.7% to 57.4%	Roggensack (1977)
11	$1.5x10^{-3}$ to $7.0x10^{-3}$	Tested	9 fine grained soils sites from Norman Wells to Zama: W/C 25% to 30%, Pl 17% to 25%, Ll 35% and 70%	Hanna & McRoberts (1988)

2 SOIL SAMPLING AND TESTING

Soil samples were recovered from eight active landslide locations in the Mackenzie valley, NWT, as shown in Figure 1. The northern sites are in Inuvialuit Settlement Region and are depicted as I1, I2 and I3. The southern sites are in Gwich'in Settlement Region and are depicted as G1 to G10.

Soils were sampled with shovel and other hand held tools from test plots and landslide scarp walls. A total of 16 samples (tin size 50 mm high and 75 mm diameter), one block sample (30 x 30 x 30 cm) and two remoulded samples were collected. The block sample, G1-TP6, was taken from a depth of 60 cm near landslide G1, from which two specimens, G1-TP6 I and G1-TP6 II, were extracted at different depths. A total of 20 samples were collected for testing.

The tin samples were taken mostly from the bottom of the active layer along freshly exposed landslide headwalls. The tin samples were collected in a relatively undisturbed state from horizontal and vertical directions. The block sample was wrapped with cloth towel and sealed with paraffin wax. Grab samples were also taken from the same locations for grain size and Atterberg limits testing.

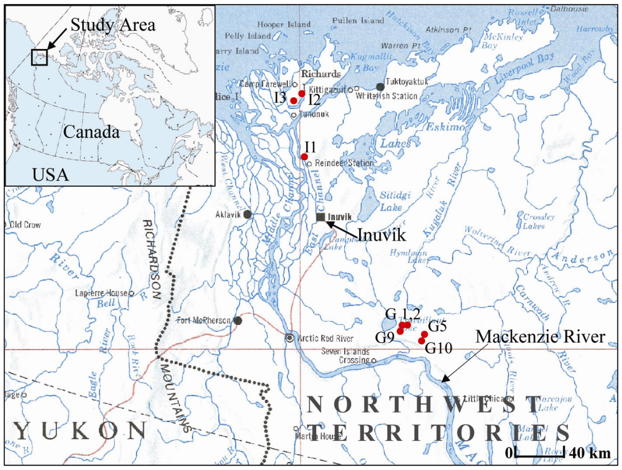


Figure 1. Location of study sites.

For testing the coefficient of consolidation, a conventional odometer (consolidometer) of 64 mm diameter and 25 mm in height was set up in the laboratory of the Geological Survey of Canada (GSC), Ottawa, Ontario. In Table 2, samples #1, 2, 7, 8 and 17 to 20 were tested in the GSC laboratory. Other samples were tested in geotechnical laboratories outside the GSC. Samples were trimmed with minimum disturbance and placed in the consolidometer for testing. The testing procedure was in accordance with ASTM D2435-04 (2004), incremental loading system B. The testing started with a vertical pressure as low as 2 kPa for samples tested outside the GSC and 4.8 kPa at the GSC. The low load was applied to observe consolidation behavior of soils at shallow depth where active layer thawing takes place. Natural thawing depth normally ranges from a few centimeters to about 1.5 m in the study region as observed during field investigations. A maximum of up to 1,280 kPa vertical pressure was applied to cover a higher range of overburden pressures. Sample deformation was recorded with a transducer of 0.001 mm precision. A digital readout unit was used to record data every 3 seconds. A set of vertical deformation and square root of time curves were drawn and coefficients of consolidation, C_v, were computed following ASTM D 2435-04 (2004) and Taylor (1948).

3 TEST RESULTS

A list of tested samples is shown in Table 2. Routine grain size and Atterberg limits tests were carried out for identification of plasticity and fines contents for most of the samples. A grain size distribution chart is shown in Figure 2. The soils ranged from silty clay or clayey silt with sand. The materials from the southern study sites are typically finer than those from the northern sites.

Table 2. Geotechnical index properties of tested samples

#	Sample Identification	Depth (cm)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
1	I1 Vertical	90	36	13	23
2	I1 Horizontal	90	36	13	23
3	I2 Horizontal	70	34	16	19
4	I3 Vertical	70	35	15	19
5	I3 Horizontal	70	35	15	19
6	G1 Vertical	110	62	26	36
7	G1 Vertical	120	62	26	36
8	G1 Horizontal	120	62	26	36
9	G2 Vertical	90	60	26	35
10	G2 Horizontal	90	60	26	35
11	G5 Vertical	70	51	24	27
12	G5 Horizontal	70	51	24	27
13	G9 Vertical	50	62	27	35
14	G9 Horizontal	50	62	27	35
15	G10 Vertical	80	-	-	-
16	G10 Horizontal	80	-	-	-
17	Block G1-TP6 I	52	59	32	27
18	Block G1-TP6 II	54	59	32	27
19	G1 Remoulded I	-	64	28	37
20	G1 Remoulded II	-	64	28	37

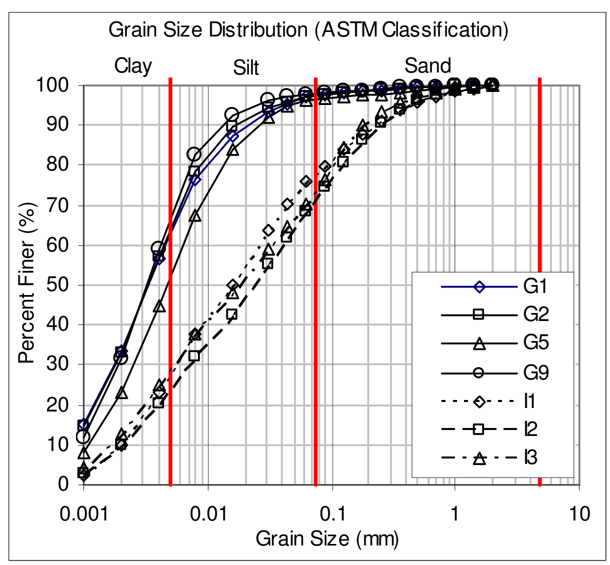


Figure 2. Grain size distribution of selected samples.

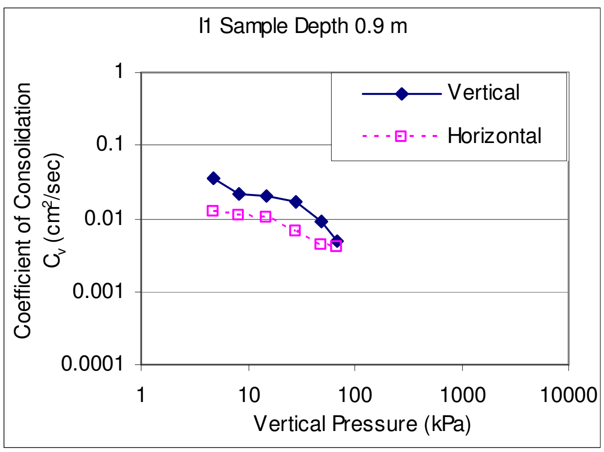
Equation 4 (Taylor 1948), given below, is used for calculation of coefficient of consolidation.

$$c_v = \frac{T_{90} H^2}{t_{90}} \qquad [4]$$

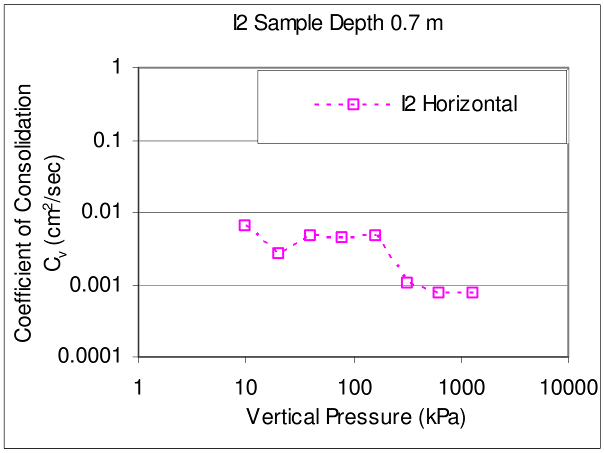
Where, T_{90} is a dimensionless time factor for 90% consolidation and equal to 0.848. The notation t_{90} is the required time for 90% consolidation and H is the drainage length, half of the specimen height for this stage of testing (1.25 cm).

Coefficient of consolidation versus vertical pressure curves are shown in Figures 3 to 6. The relations shown in Figure 3 (a) to (c) and Figure 4 (a) to (f) are for samples from the northern and southern regions, respectively. Figure 5 compiles all the C_v data for the undisturbed samples from both the northern and the southern sites for comparison purpose. Figure 6 shows the C_v values of two remoulded samples from the southern site G1.

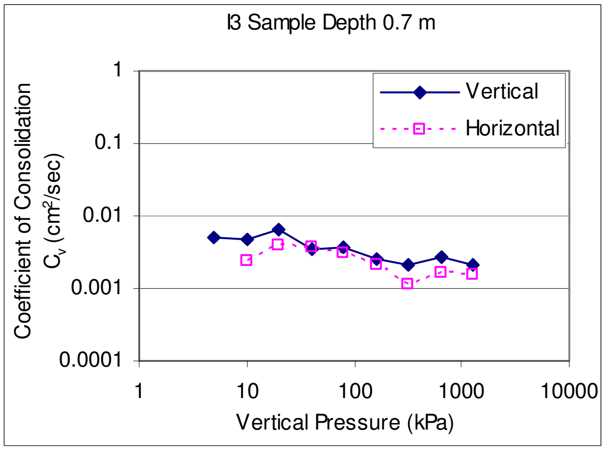
As seen from Figure 3, the coefficient of consolidation values for the northern undisturbed samples range from 7×10^{-4} to 2×10^{-3} cm^2/sec for the tested maximum vertical pressure of 1,280 kPa. The C_v values for the southern undisturbed samples at similar vertical pressure are from 2×10^{-4} to 5×10^{-4} cm^2/sec as shown in Figure 4. There is little difference between the vertical and horizontal sample results for both northern and southern sites. The tested values are comparable with those summarized in Table 1.



(a) I1 vertical and horizontal samples – depth 0.9 m



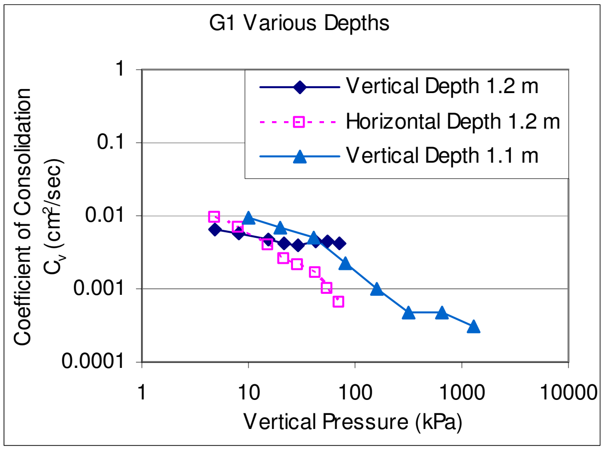
(b) I2 horizontal sample – depth 0.7 m



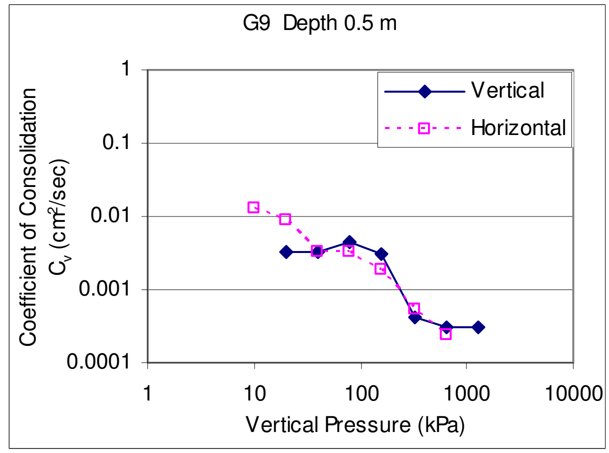
(c) I3 vertical and horizontal samples – depth 0.7 m

Figure 3. (a) to (c) Coefficient of consolidation of samples recovered from the northern sites.

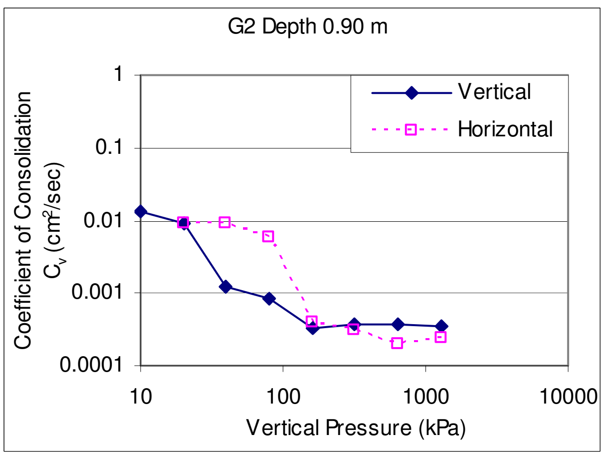
It is noted from Figure 5 that, at vertical pressures lower than about 100 kPa, the initial C_v values fall within the same range for both the southern and the northern sites. However, the southern sites have lower C_v values at vertical pressures greater than 100 kPa. This is likely due to the difference in fines contents and plasticity between the samples of the two regions. As seen from Figure 2 and Table 2, soils from the southern sites contain more fines and show higher plasticity compared to those from the northern sites.



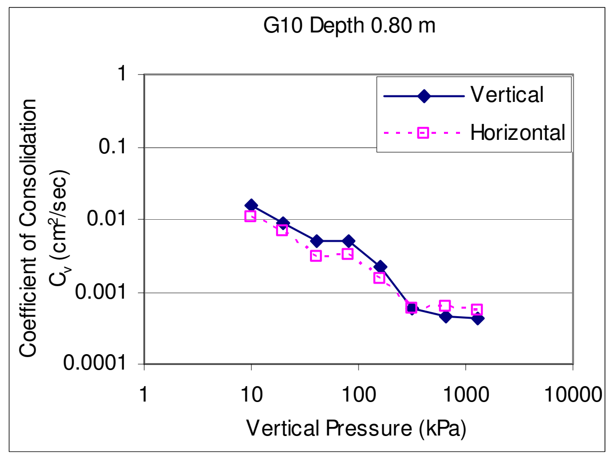
(a) G1 vertical and horizontal samples – depth 1.1 m and 1.2 m



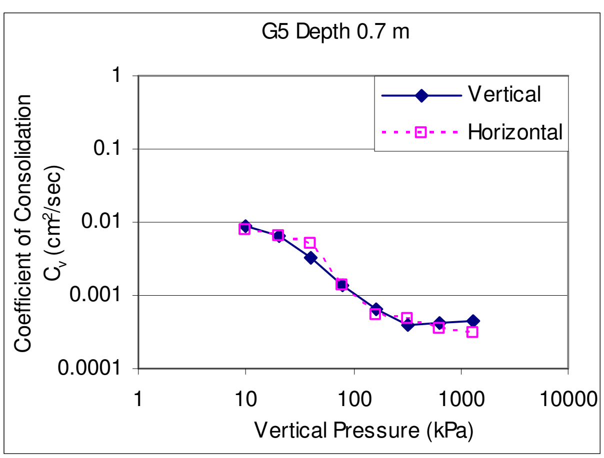
(d) G9 vertical and horizontal samples – depth 0.5 m



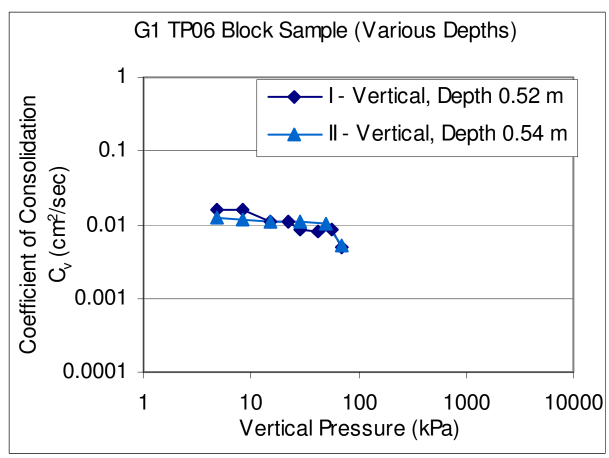
(b) G2 vertical and horizontal samples – depth 0.9 m



(e) G10 vertical and horizontal samples – depth 0.8 m



(c) G5 horizontal and vertical samples – depth 0.7 m



(f) G1 vertical samples from a block sample at TP06 – depth 0.52 m and 0.54 m

Figure 4. (a) to (f) coefficient of consolidation of samples recovered from the southern sites.

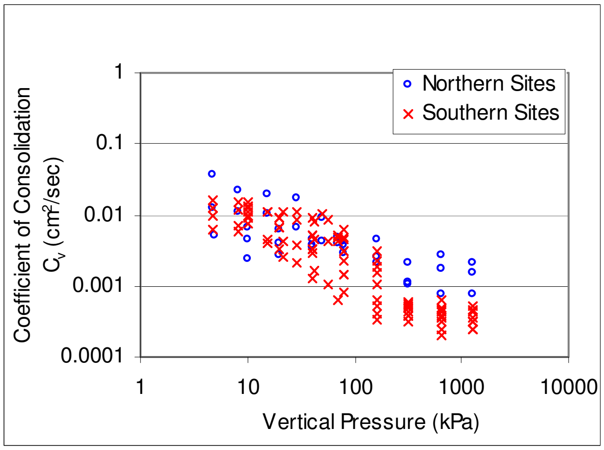


Figure 5. Comparison of coefficient of consolidation between samples from northern and southern regions.

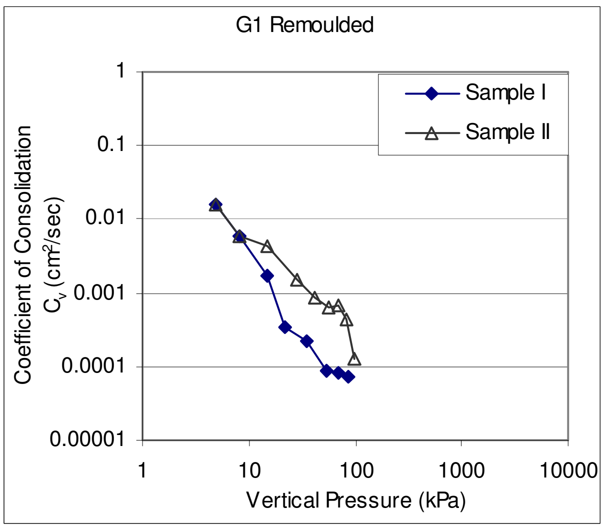


Figure 6. Coefficient of consolidation for remoulded samples recovered from site G1.

By comparing Figure 6 with Figures 4 and 5, it is noted that the C_v values for the remoulded samples are lower than that observed for the undisturbed samples. At a vertical pressure of 100 kPa, for example, the remoulded samples showed C_v values of $7x10^{-5}$ and $1x10^{-4}$ cm^2/sec, while that of the undisturbed samples varied from $5x10^{-4}$ to $5x10^{-3}$ cm^2/sec (Figure 5), which is about an order of magnitude difference. This is perhaps due to the effect of the soil structures developed from freezing and thawing of the undisturbed samples.

4 CONCLUSIONS

Coefficient of consolidation, C_v, for 20 soil samples from 8 active landslide sites in two regions in the Mackenzie valley have been presented. Most of the samples were collected from near the bottom of the active layer at the landslide head scarps. The samples from the southern region are finer than those of the northern region. The C_v results are fairly consistent within each group (region) of samples. Geotechnical index properties of the soils tested are also presented. The index properties can be used to compare with similar soils for the purpose of estimating their C_v values based on this set of data. The tested C_v values are believed to be representative of the fine grained soils subject to freeze-thaw effect in the Mackenzie valley region. The data contribute a knowledge base for thaw consolidation analysis of fine grained soils in permafrost, in which coefficient of consolidation is the most sensitive parameter.

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