Slope Observations and Field Mapping to Verify the Stability of Slopes near Kitimat, BC

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ABSTRACT
Landslides and slope instabilities have previously occurred in the vicinity of Kitimat, British Columbia in sensitive or quick clays of glaciomarine origin. The assessment of slope stability has been one of the key challenges in this area due to the difficulty in reliably estimating the shear strength parameters as well as other factors that influence slope stability. Future developments along in this area, necessitate the prediction of slope performance. As an alternate verification approach, reconnaissance of the slopes along some of the Forestry Service Roads was performed and detailed notes of the slope configuration along with signs of instability or distress were recorded at numerous locations. The collected data from the site is reduced and presented graphically to provide insights into the anticipated performance of the slopes.

RÉSUMÉ
Des glissements de terrain ont déjà eu lieu dans la région de Kitimat, en Colombie-Britannique, dans des formations d'argiles sensibles d'origine glaciomarine. L'évaluation de la stabilité des pentes est l'un des défis dans cette région vue la difficulté à estimer de façon fiable la résistance en cisaillement, ainsi que d'autres caractéristiques clés influençant la stabilité des talus d'argile sensible. Les projets de cette région nécessitent la prédiction de la performance des pentes. Comme approche de vérification, une visite de reconnaissance de plusieurs talus le long des routes forestières de la région a été réalisée. Ainsi, des notes détaillées sur la configuration des talus, avec des signes d'instabilité ou de détresse, ont été enregistrées dans de nombreux endroits. Les données recueillies du site ont été représentées graphiquement afin d'avoir des indices permettant d'anticiper la performance des pentes.

1 INTRODUCTION

The assessment of slope stability and prediction of slope performance has been one of the key geotechnical challenges in the Kitimat/Terrace area due to the presence of sensitive glaciomarine soils and difficulty in estimating shear strength parameters along with various other factors that typically control the stability of slopes.

Many historical earthflows and instabilities have occurred in the Kitimat/Terrace corridor. While a significant number of these instabilities date back to a wet period from approximately 2000 to 3000 years ago (Geertsema and Schwab, 1997), five major earthflows and slides have occurred since 1950. The common theme among these instabilities is the presence of sensitive, highly sensitive or quick clays of glaciomarine origin and the retrogressive nature of the slides. The approximate location of these major historical landslides are shown in Figure 1.

The high frequency of historical instabilities in this area is consistent with the theory of valley formation in Canadian clay deposits proposed by Lefebvre (1986). He divides valley formation in clay deposits into three phases. The early phase typically involves incision into the clay deposit without influencing the hydrogeology of the underlying coarse-grained layers. The intermediate phase is characterized by deep valley walls and the presence of artesian pressures in the underlying coarse-grained deposits. The third phase is characterized by incision into the underlying coarse-grained material. While only small and relatively infrequent instabilities are anticipated during the early and late phases of valley formation, the intermediate phase of valley formation generally involves larger and more frequent landslides and slope instabilities. Creeks in the vicinity of Kitimat appear to be in the early and intermediate stages of valley formation (Geertsema et al. 2006) and therefore large and more frequent instabilities are possible.

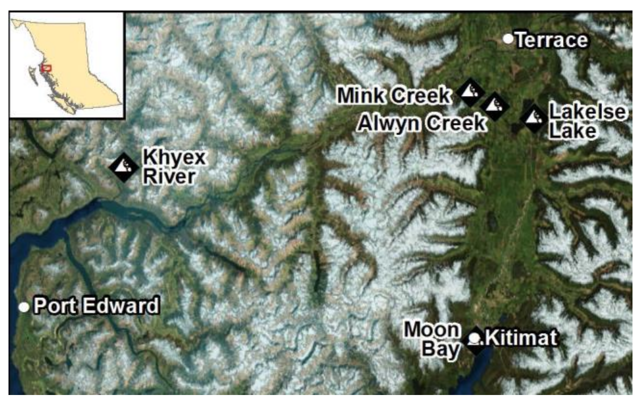

Figure 1. Historical Landslides in the Vicinity of Kitimat/Terrace, BC.

Furthermore, global circulation models in general predict a warmer and wetter climate for this region in the future, which may contribute to increased slope instability.

New facilities are planned to be constructed at the vicinity of Kitimat and Bish Creek (10 km south of Kitimat). Construction of cut slopes in fine-grained and potentially sensitive clays/silts and assessment of natural slopes will be required as part of the future developments. In light of these challenges and the anticipated new developments, a field mapping program was performed to record observable factors that impact slope performance and to verify the results of geotechnical slope stability analyses.

2 BISH CREEK

Bish Creek discharges into open waters approximately 10 km south of Kitimat (see Figure 4). The terrain in this region has been largely shaped by glacial erosion from the repeated advance and retreat of ice sheets over the Quaternary Period (i.e. 2.6 million years ago to present) and in general comprises rugged mountainous areas bounded by large, deeply incised valleys and fjords.

The general area is accessed via the Bish Forest Service Roads (FSR) and other secondary logging roads, which generally comprise single-lane, approximately 4 to 6 m wide, gravel surfaced roads that were originally constructed in 1970s.

2.1 Geology

The overburden sequence generally dates back to the final stages of the last glaciation (i.e. approximately 12,000 years ago) and subsequent deposition during post-glacial (i.e. Holocene) time. At the time this area was de-glaciated, relative sea levels were approximately 200 m above the present datum due to the glacio-isostatic depression of the earth's crust by the weight of the Cordilleran ice sheet that covered British Columbia.

Along Kitimat Arm, complex assemblages of glacial till and coarse glaciomarine sediments were deposited along the valley bottom in close proximity to the decaying, fluctuating glacial margin, and were variably overridden by ice. As the glacial margin retreated towards the present Kitimat town site, finer-grained glaciomarine deposits (sand, silt and clay) were deposited in the sediment-laden waters of Kitimat Arm (Clague, 2014).

As the glacial front retreated north of Kitimat towards Terrace, the crust beneath this area rapidly rebounded (Hetherington et al. 2004). Surfaces up to about 200 m above sea level that were formerly inundated by the sea became dry land. As relative sea level fell, Bish Creek incised the glaciomarine soil sequence, creating terraces at successively lower elevations.

The salinity of the water was different at different locations and some pockets of the glaciomarine silts and clays were deposited in high salinity water and formed meta-stable random particle structures with strong inter-particle bonds. Subsequent post-glacial fluvial downcutting and freshwater leaching of the glaciomarine silt and clay has resulted in the development of highly sensitive clays/silts in some areas.

2.2 Geotechnical Properties

Soil conditions generally comprise of topsoil / organics over fine-grained soil consisting of clayey silt to silty clay over coarse-grained glacial deposits or bedrock. Clayey silt to silty clay deposits, where present also contain varying amounts of sand and gravel. The fine-grained soil ranges in thickness from less than 1 m to more than 50 m in the general area. Moisture contents and Atterberg Limit data corresponding to the fine-grained material were previously obtained by others and are summarized in Table 1.

Table 1. Moisture Content and Atterberg Limit Data of Fine-Grained Materials

Parameter	Typical Range	Average	Standard Deviation
Liquid Limit	29 to 44	36	7
Plastic Limit	16 to 22	19	3
Plasticity Index	16 to 28	22	6
Liquidity Index	0.3 to 1.0	0.7	0.4
Moisture Content	28% to 38%	33%	5%

Data presented in Table 1 were obtained from 21 soil samples collected during the subsurface exploration. Hydrometer tests performed on 5 soil samples indicated a clay content (< 0.002 mm particle size) ranging from 33% to 53% with an average clay content of 42%.

3 PREVIOUS LANDSLIDES AND CASE HISTORIES

The following landslides are among those that have been documented in the vicinity of Kitimat since 1950:

- *Alwyn Creek - June 1953:* A landslide occurred in glaciomarine terrain south of Terrace during construction of a rail crossing across Alwyn Creek, burying bulldozers and other construction equipment. A curved railway trestle was later constructed to bypass this area (Geertsema et al., 2008).
- *Lakelse Lake - May and June 1962:* Two massive, extremely rapid landslides, measuring 11 to 15 million cubic metres, occurred in glaciomarine terrain along the east side of Lakelse Lake during construction of Highway 37. The slides, which were likely triggered by the placement of embankment fill, flowed into Lakelse Lake carrying vehicles and equipment, and destroying adjacent sections of the highway (Geertsema and Schwab 1997 and Evans 1982).
- *Mink Creek - Between December 1993 and January 1994:* A landslide occurred in sensitive glaciomarine clay along the bank of Mink Creek, located west of Lakelse Lake. The slide rapidly retrogressed from a small bank failure into a large landslide encompassing an area of about 23 hectares. The slide mass flowed approximately 1000 m downstream along Mink Creek and impounded water to a depth of about 10 m behind the resulting debris dam (Geertsema and Schwab 1997, Geertsema and Torrance 2005 and Geertsema et al. 2006).
- *Khyex River - November 2003:* Although not in the general vicinity of Kitimat, a landslide occurred in similar soil conditions (i.e. fine-grained deposits of glaciomarine origin) and severed about 350 m of natural gas pipeline 35 km east of Prince Rupert.

The event occurred at Khyex River about 6.8 km upstream from its confluence with Skeena River. The landslide encompassed 32 hectares, infilled the river and caused flooding upstream of the depletion zone (Schwab et al. 2004).

- *Moon Bay - April 1975:* A submarine landslide occurred during fill placement and construction of a small barge wharf at Moon Bay. The wave generated by the submarine landslide damaged the dock, destroyed dolphins at the Eurocan shipping dock and damaged shore installations about 3 km across the inlet on the east shore.

With regards to older events, Geertsema and Schwab (1997) present geomorphologic evidence of numerous prehistoric landslides in glaciomarine terrain between Kitimat and Terrace. Based on the work performed by Geertsema and Schwab (1997), prehistoric slope instabilities are particularly frequent in the vicinity of Mink Creek, the foreslope of the Onion Lake delta, the Nalbeelah Wetland complex, and along Cecil Creek and Deception Creek. The Bish Creek valley, however, was not part of the area studied by Geertsema and Schwab (1997).

It is notable that several of the documented instabilities in the Kitimat area occurred due to construction activities and associated earthworks, which further necessitates the assessment of the natural and cut slopes.

4 FACTORS INFLUENCING THE SLOPE STABILITY

4.1 Slope Features

Factors that generally contribute to the instability of slopes can be subdivided into external, internal and intrinsic categories (Burland et al. 2012). Figure 2 presents the most common factors giving rise to slope instability, grouped according to these categories.

While defining and estimating the external factors are relatively straightforward, estimating the internal and intrinsic factors is more difficult and in most cases requires subsurface exploration as well as engineering judgement. Understanding the effect of various internal and intrinsic factors on the overall stability of a particular slope is typically cumbersome and may require sensitivity analyses and additional research.

The most common errors in evaluating slope stability arise from the incorrect assessment of the following (Burland et al. 2012):

- Design values for shear strength including the mode of failure (i.e. drained versus. undrained);
- Groundwater regime and pore pressures during the life of the slope;
- Foundation soil layering and effect of weak layers including failure to recognize their existence and/or neglecting their orientations; and
- Failure geometry (i.e. only assessing circular slip surfaces).

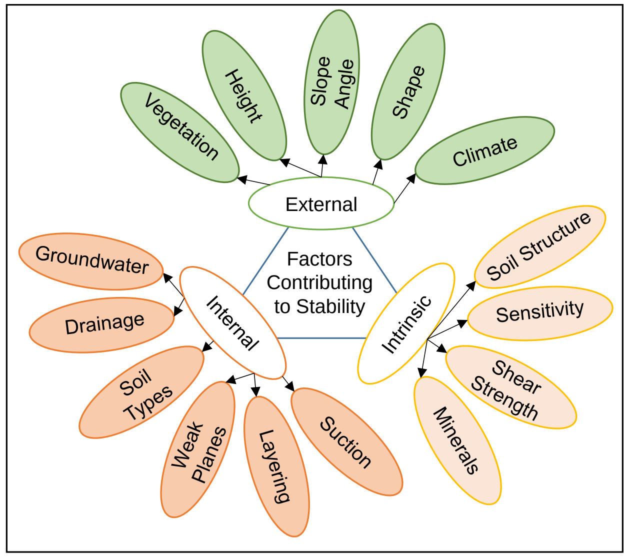

Figure 2. Factors Contributing to Instability of Slopes

Groundwater conditions and shear strength of the soil body greatly influence the stability of soil slopes. However, properly estimating these factors is usually difficult and requires considerable judgement and experience. Groundwater should represent the in situ conditions during wet and dry seasons and shear strength should be estimated with due consideration to the mode of shearing (i.e. drained versus undrained). Experience shows that laboratory measured peak shear strength parameters are often poor choices for estimating the stability of slopes (Burland et al., 2012). Furthermore, variations in soil composition makes it very difficult to estimate the shear strength parameters solely based on soil descriptions.

Limit equilibrium analysis is typically performed for evaluation of slope stability. However, in light of the challenges associated with estimating the aforementioned internal and intrinsic factors, the current field mapping program was performed to verify and augment the limit equilibrium analyses for the future developments in the general area.

4.2 Failure Modes

Commonly encountered modes of slope failure are presented in Figure 3. The main distinction between slope movement and slope failure is that in the case of slope movement, the moving mass does not detach from the slope body. Rock fall and soil slides can turn into flow failures if sufficient mass is generated from the failure and the moving mass follows the existing topography during the movement, similar to the flow of thick fluids.

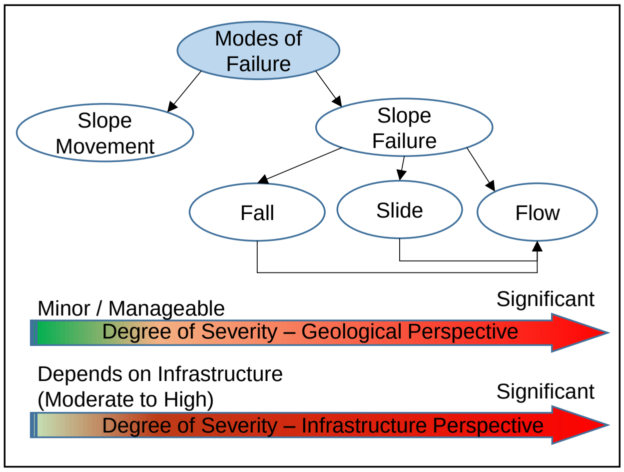

Figure 3. Modes of Failure and Severity

The consequence and degree of severity associated with a slope instability is judged differently from a geological perspective and geotechnical/infrastructure perspective. From a geological standpoint, slope movements represent minor or manageable severity. However, from a geotechnical / infrastructure perspective small slope movements could still result in costly damages.

5 METHODOLOGY

The available aerial photographs and LiDAR survey data were initially reviewed to identify and outline key areas of interest. These areas of interest included arcuate topographical landforms thought to represent existing or ancient slope failures back scarps, gullied glaciomarine terrain with the potential for associated soil exposures and slope instabilities, as well as large rock slopes and bedrock outcrops potentially subject to rock fall and debris slide hazards.

Field mapping was completed in December 2014 by a representative from Tetra Tech EBA. Mapping was completed utilizing an iPad pre-loaded with available LiDAR imagery and aerial base maps, a handheld GPS, camera and compass clinometer to identify and map various slopes and Points of Interest (POI). The general locations of the POIs are presented in Figure 4.

Slope height measurements were performed using a laser range finder. Shallow 1 m deep hand-augured holes with shear vane testing of fine-grained soils were completed at some locations to provide information on subsurface soil conditions. The slopes were differentiated and grouped into natural slopes and cut slopes (i.e. constructed cut slopes)

Where failed or highly distressed slopes were noted, the original (i.e. pre-failure) inclination of the slope was estimated based on the surrounding slopes.

The following features were recorded at POIs:

- External features including slope height, slope angle and vegetation;
- Observation of surficial water and seepage from the slopes;
- Subsurface soil conditions, estimated shear strength, etc. where feasible;
- Signs of instability. The slopes were categorized based on the following observed performance:
  - <u>*Good Performance:*</u> No obvious signs of distress.
  - <u>*Moderate Distress:*</u> Sloughing and erosion of the slope surface.
  - <u>*Major Distress:*</u> Evidence of previous slides and failures.
  - <u>*Unknown:*</u> Areas where slope performance could not be readily assessed (e.g. logged trees obscuring the slope surface or small head scarps along with the presence of mature vertical trees on the slope).

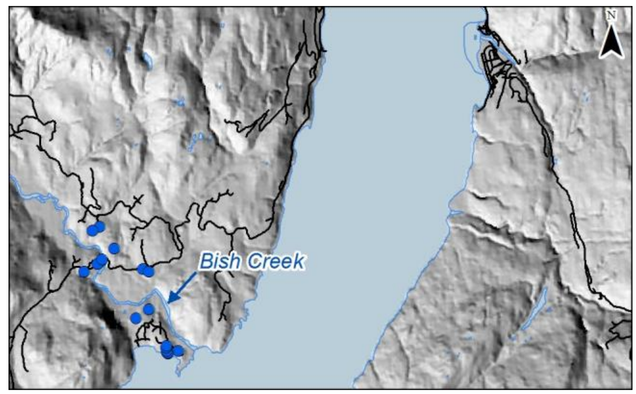

Figure 4. General Area of the Mapped Slopes. Blue dots represent the mapped points of interest.

6 RESULTS

Table 2 summarizes the number of data points obtained during the field mapping. The data points in Table 2 mostly correspond to the silt/clay slopes. Rock slopes were not included in the database, however, a few sand, sand/silt and sand/clay slopes are included in the database.

Table 2. Number of Slopes Mapped

Performance Category	Cut Slopes	Natural Slopes
Good Performance	0	2
Moderate Distress	8	9
Major Distress	2	6
Unknown Distress	0	2
Total	10	19

Some data gaps are present within the collected data. Namely, cut slopes with good performance were not mapped and steep natural slopes are not present in the dataset (possibly because the latter do not occur).

The slope angles versus heights corresponding to all the data points are plotted in Figures 5.

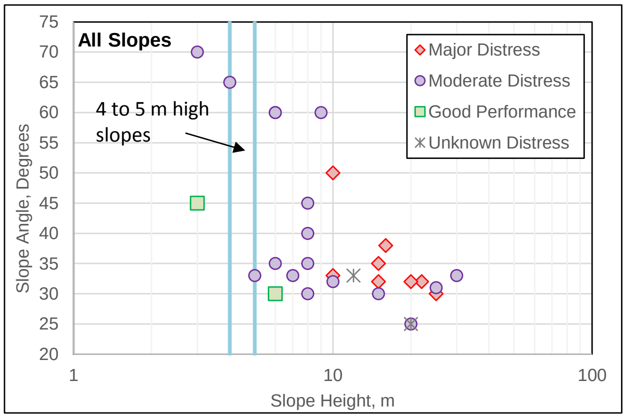

Figure 5. Mapped Data Corresponding to All Slopes

7 DISCUSSION

The results presented in Figure 5 indicate that majority of the mapped slopes were higher than 4 to 5 m. The available data points pertaining to the slopes less than 4 m in height, which are typical of engineering construction, however, are very limited in the database and the results should be interpreted with caution. Slopes between 5 m and 10 m in height generally showed moderate distress whereas slopes higher than 10 m showed a greater tendency to experience distress at higher inclinations.

7.1 General Distress Boundaries

Hoek and Bray (1981) published simplified slope stability charts, which graphically presents the relationship between factor of safety against instability, the apparent cohesion, friction angle, unit weight, the height of the slope and the inclination of the slope for different groundwater conditions.

In an attempt to better understand and group the data presented in Figure 5, Hoek and Bray (1981) charts were used along with a unit weight of 19 kN/m^3, a friction angle of 28° and a factor of safety of unity against slope instability. The friction angle (i.e. 28°) and the unit weight (i.e. 19 kN/m^3) values were inferred based on the description and geology of the overburden, the moisture and indicator test results presented in Table 1, and our experience working with similar soils. An average groundwater condition (i.e. out of five groundwater conditions proposed by Hoek and Bray 1981) was assumed and the corresponding Hoek and Bray (1981) chart was used. The average groundwater condition corresponds to a phreatic line daylighting at four times the slope height back from the toe of the slope.

The apparent cohesion of the soil material was varied until the relationship between the slope angle and slope height inferred from Hoek and Bray (1981) charts provided a good fit boundary between different distress categories as shown in Figure 6. An apparent cohesion of 10 kPa was found to provide a reasonable differentiation boundary between major distress and moderate distress categories, and an apparent cohesion of 4 kPa was found to provide a reasonable separation boundary between moderate distress and good performance categories.

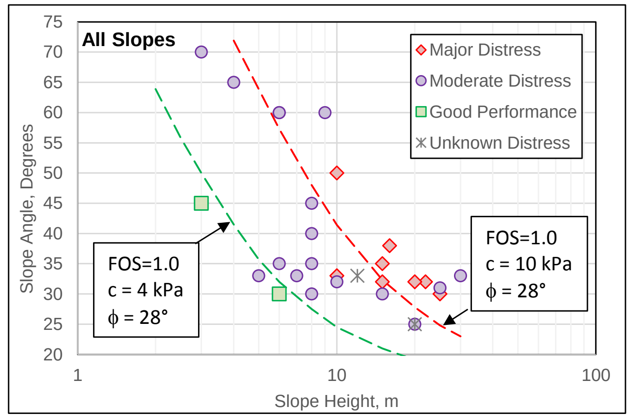

Figure 6. Boundaries Between Distress Categories Inferred from Hoek and Bray (1981).

The boundaries presented in Figure 6 imply that in general if the factor of safety is more than unity, and the friction angle is 28°, apparent cohesion is 4 kPa, unit weight is 19 kN/m^3, and for average groundwater conditions, it is likely that the slope will show good performance over time. Similarly, if the factor of safety is less than unity or close to unity, the slope will likely show signs of major distress over time. Between these two scenarios, the slopes will likely experience moderate distress over time.

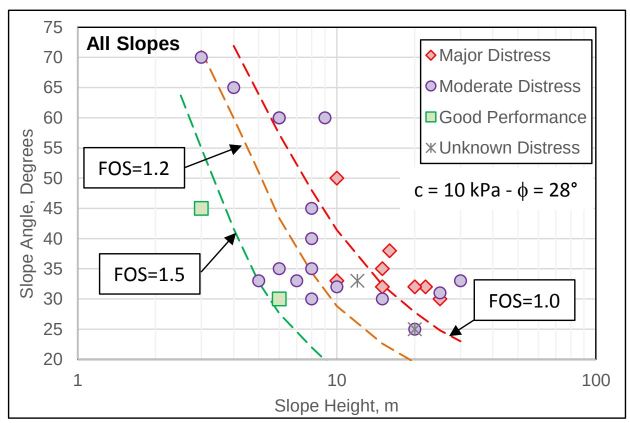

Figure 7. Relationship between the Factor of Safety and Slope Distress

Figure 7 shows the relationships obtained from Hoek and Bray (1981) stability charts, for apparent cohesion of 10 kPa and factors of safety of 1.0, 1.2 and 1.5. Other parameters were unchanged from previous assumptions. The results indicate that when the higher apparent cohesion of 10 kPa is adopted for the analyses, factors of safety of less than unity generally correspond to the major distress cases, while factors of safety of 1.5 and higher generally correspond to slopes exhibiting good performance.

The target factor of safety for slope stability analysis and design should be selected with general consideration of the reliability of the adopted shear strength parameters. The use of the apparent cohesion of 10 kPa, in this case is considered somewhat aggressive and contrary to local state of practice, given the geology of the silt/clay material, the index test results (see Table 1) and our experience working with similar soils. Therefore, a higher target factor of safety of 1.5 should be targeted to increase the likelihood of good slope performance over time. Conversely, adopting a lower target factor of safety could be justified if a less aggressive estimate of the apparent cohesion is adopted (see Figure 6).

The results also indicate that major distress should be anticipated for factors of safety of less than 1.2.

7.2 Natural Slopes

Figure 8 presents only the data points corresponding to the natural slopes along with distress boundaries inferred using the Hoek and Bray (1981) stability charts. It appears that the natural slopes with inclinations of more than about 32° and more than 10 m in height generally show major signs of distress. Similarly, natural slopes with inclinations of more than 30° and more than 5 m in height generally show moderate signs of distress.

The number of data points pertaining to steep slopes (i.e. more than 35° for higher than 10 m, and more than 40° for slopes between 5 m and 10 m) are very limited in the database. This is likely because over-steeped natural slopes do not occur; however, this could not be confirmed using the available data.

The possible boundary/limit of the natural slopes with respect to inclination and height is presented by a solid black line in Figure 8.

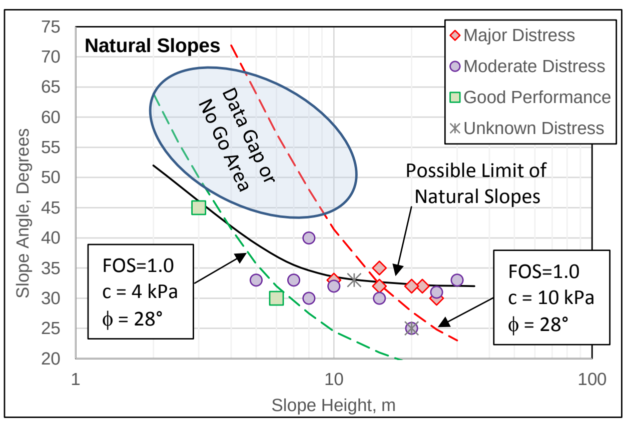

Figure 8. Mapped Data Corresponding to Natural Slopes

7.3 Cut Slopes

Figure 9 presents only the data points corresponding to the cut slopes, which generally show moderate or major signs of distress. A gap in the collected data is noted pertaining to the cuts slopes with good performance. Steeper slopes are noted among the cut slopes.

Previous studies show that cut slopes in silt/clay material are generally most stable immediately after the construction due to the generation of negative pore pressures and apparent cohesion but typically become less stable over time. Implementation and construction of stabilizing measures such as toe berms, drains, etc. would likely compensate for the deterioration of internal/intrinsic stability factors.

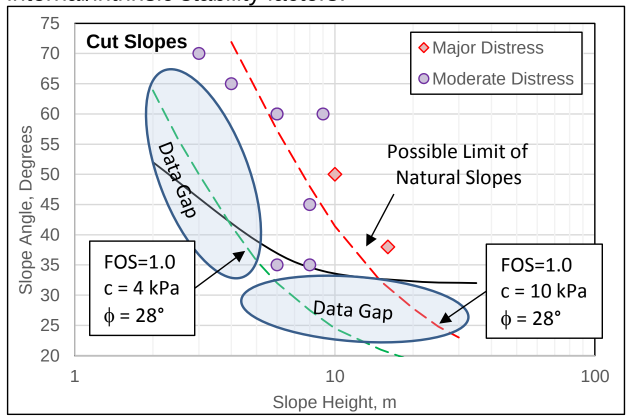

Figure 9. Mapped Data Corresponding to Cut Slopes

In the absence of stabilizing measures, however, it is expected that slopes plotting above the possible limit of natural slopes would deteriorate over time until they reach the limiting boundary. Therefore, when designing cut slopes, which plot above the possible limit of natural slopes, rigorous exploration, verification and design must be undertaken before construction.

7.4 Effect of Seepage

The effect of seepage on the slope conditions are presented in Figure 10. The data is grouped into the slopes at which seepage was noted as well as the slopes at which no seepage was noted. At five locations no observations regarding surface drainage or seepage was recorded and the corresponding data points were not presented in Figure 10.

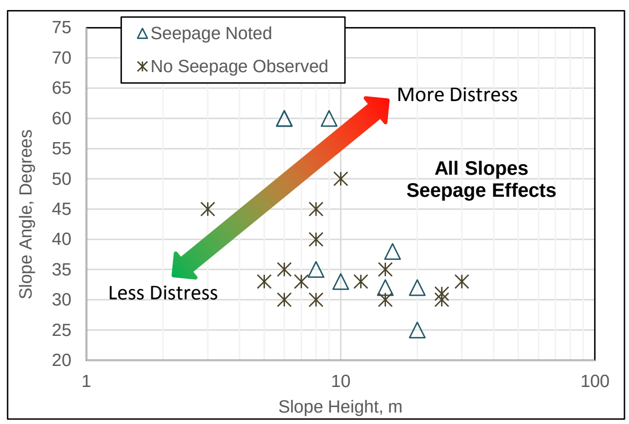

Figure 10. Effect of Drainage on Slope Conditions

The results indicate that the slopes with seepage noted at the surface are more likely to show signs of distress than the slopes that showed no visible sign of seepage.

8 SUMMARY AND CONCLUSION

The results of the field mapping program can be used as a secondary verification tool to assess the performance of natural and cut slopes in the Kitimat area.
The results indicate that:

- Slopes with a factor of safety of more than unity obtained from Hoek and Bray (1981) stability charts, while assuming a friction angle of 28°, apparent cohesion of 4 kPa, unit weight of 19 kN/m^3 and average groundwater conditions, are likely to perform well without showing moderate to major signs of distress (Figure 6).
- The target factor of safety should be commensurate with the reliability of the shear strength parameters. The results show that if high apparent cohesion is adopted for the stability analysis at the general area, a higher target factor of safety should be adopted. A higher target factor of safety of 1.5 was found to represent the slopes with good performance if an aggressive apparent cohesion of 10 kPa is adopted while all other variables are kept unchanged (Figure 7).
- It appears that natural slopes in the general area have an upper limit boundary line presented in Figure 8. The presence of this line should be further verified by obtaining additional data (Figure 8). However, in the absence of additional data, cut slopes plotted above the possible limit of natural slopes should be subjected to more rigorous exploration, verification and design before construction (Figure 9).
- An anticipated warmer and wetter climate in the future will likely provide conditions similar to 2000/3000 years ago, when slope instabilities were frequent in the area. This signifies the importance of proper drainage design in the future performance of the slopes and preventing the saturation of the soil to the extent possible.

9 LIMITATIONS

The limited number of data points and the gaps in the database (Figures 8 and 9) should be considered and the appropriateness of the inferred distress boundaries should be judged on a case by case basis. The methodology presented here only provides a secondary verification tool and is not intended as a substitute for more rigorous geotechnical exploration, analysis and design.

The identified data gaps of the current study are shown on Figures 8 and 9. A subsequent field mapping program is currently being executed with the aim of filling the gaps in data. When available, the results of this subsequent mapping program will be added to the current database to better delineate the distress boundaries plotted on Figure 6 and to verify or revise the possible limit of natural slopes.

10 ACKNOWLEDGEMENT

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