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Assessment and Mitigation of Landslide Hazards in Sensitive Clay

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ABSTRACT
In some areas of northern countries highly sensitive glaciomarine clays deposited in estuaries and fjords are susceptible to catastrophic retrogressive landslides that are typically triggered by natural events or by human events. This sensitive glaciomarine clay hazard has been a concern on recent pipeline projects in British Columbia, Canada, particularly those natural gas pipelines associated with LNG (Liquefied Natural Gas) export terminals; however, it could become an issue for pipelines in other coastal areas of these northern countries where oil and gas development is relatively active. Pipelines could be routed over these glaciomarine clay deposits by identifying and mapping areas susceptible to retrogressive landslides. Landslide risk can be mitigated either by micro-routing or by modification of the terrain and/or the construction procedures. Geospatial data was leveraged in a geoprocessing algorithm within a GIS to map susceptible areas using LiDAR. These areas are screened based on available geotechnical and geological information to refine both the mapping and the assessment of risk. Methods of mitigation, particularly through terrain modification and construction earthworks design, are also presented.

RÉSUMÉ
Dans certaines régions des pays nordiques, les argiles glaciomarines très sensibles déposées dans les estuaires et les fjords sont susceptibles de glissements de terrain rétrogrades catastrophiques qui sont généralement déclenchés par des événements naturels ou humains. Le risque de cette argile glaciomarine sensible a préoccupé les récents projets de gazoducs en Colombie-Britannique, au Canada, en particulier les gazoducs associés aux terminaux d'exportation de GNL (gaz naturel liquéfié); cependant, cela pourrait devenir un problème pour les gazoducs dans d'autres régions côtières de ces pays nordiques où le développement pétrolier et gazier est relativement actif. Les gazoducs pourraient être acheminés au-dessus de ces dépôts argileux glaciomarins par identifier et surveyer les zones susceptibles de subir des glissements de terrain rétrogrades, et atténuer le risque de glissement de terrain par micro-routage ou par modification du terrain et / ou des procédures de construction. Les données géospatiales ont été exploitées dans un algorithme de géotraitement au sein d'un SIG pour surveyer les zones sensibles à l'aide de LiDAR. Ces zones sont triées suivant la base des informations géotechniques et géologiques disponibles pour affiner à la fois la cartographie et l'évaluation des risques. Des méthodes d'atténuation, notamment par la modification du terrain et la conception des terrassements de construction, sont également présentées.

1 INTRODUCTION

Sensitive clays are highly susceptible for initiating large flowing landslides and this has been a serious geotechnical problem for pipeline projects. Many landslides in sensitive clay have occurred and some are presently active in northern countries as result of human, river, and earthquake activities. These landslides are mostly large and flow out over a vast area. The Rissa Landslide, one of the biggest and most important landslides, occurred on April 29, 1978 in Central Norway and covered an area of 330,000 m^2. The initial slide involved only 200 m^3 of sediment and subsequently grew to 5-6 million m^3 in a few hours through retrogressive sliding (Gregersen 1981). Landslides in sensitive clay can be found in Eastern and Western Canada, even in areas with very little relief. Since 1973, at least 18 rapid large landslides with over 500,000 m^3 debris flows and runouts longer than 1 km have occurred in northern British Columbia (Geertsema et al. 2006). However, thousands of smaller undocumented landslides can be identified on air photos.

Canada has one of the largest pipeline networks with a total length of over 830,000 km of different types of pipelines (CEPA 2015). Among them, many pipeline projects have been constructed in British Columbia and some are currently under design. Landslides have always been considered a major hazard for pipeline projects in this province. As an example, on November 2003, the Khyex River landslide, 35 km east of Prince Rupert in northwestern BC, displaced approximately 4.7 million m^3 of material and extended over an area of 32 ha, severing a natural gas pipeline. As a result of this landslide, Prince Rupert residents were without natural gas heat for 10 days (Schwab et al. 2001).

In this paper, an approach for mapping landslides and their risk assessment based on a geoprocessing algorithm within GIS (Geographic Information System) software is presented. The approach maps areas susceptible to retrogressive landslides from the combination of a LiDAR-based digital elevation model (DEM) and surficial terrain polygons. The application of this approach can subsequently be used in pipeline routing and supplementing the engineering design of pipeline systems.

2 SURFICIAL GEOLOGY OF BRITISH COLUMBIA

In terms of geology, British Columbia is considered a diverse province with different geological features of mountain ranges and incised plateaus. Bedrock and surficial materials vary greatly through this province. In general, surficial materials have been eroded from bedrock and re-deposited by natural agents such as glaciers, water, wind, etc. Till, glaciofluvial, glacio-lacustrine, glaciomarine, eolian and colluviums are the most common surficial deposits in British Columbia. Till is a nonsorted, nonstratified, relatively loose to compact drift with a wide range of mixed grain sizes from clay to boulders, deposited directly by glaciers. Glaciofluvial deposits are sorted and stratified materials consisting of coarse to medium grained sand and gravel, poorly to well sorted and bedded, with numerous cobbles, boulders, and lenses of till, moved by glaciers and deposited by streams flowing from the melting ice. Glaciolacustrine deposits are commonly silt and clay material carried in the suspended load and deposited in lake water that is exposed later either by lowering of the water level or elevation of the land. Glaciomarine sediments are medium to fine-grained material deposited by glacial meltwater in an ocean environment (Mullard 1996 and Sauer and Elder 1982). In general, landslides may occur in any of these deposits; however, valleys eroded in glaciomarine deposits with sensitive clay are particularly susceptible to flow sliding. More detailed discussions about glaciomarine deposits, their characteristics, and landslides occurring in these materials are presented in the following sections.

3 GLACIOMARINE DEPOSITS AND THEIR CHARACTERISTICS

Glaciomarine sediments originated in glaciated lands and were then transported to the oceans by glaciers. These sediments were mostly deposited during the retreat of the most recent Pleistocene ice sheet and are highly susceptible to large destructive landslides. Glaciomarine sediments are mostly fine-grained silty clay to clayey silt. A category of these sediments, also called sensitive clay, has high sensitivity and low remolded shear strength. These unusual geotechnical properties of glaciomarine sensitive clay often adversely affect design and construction activities.

In general, sensitivity in clay is defined as the ratio of the shear strength of undisturbed clay to its remolded shear strength and is expressed as a dimensionless number. Figure 1 and 2 show the schematic stress-strain curve of brittle and quick clays respectively. As shown in Figure 1, soil sensitivity can be calculated using the following equation:

$$s_t = \frac{s_u}{s_{ur}} \qquad [1]$$

Clays with extremely low remolded strength likely have very high sensitivity and in most cases flow when remolded. For example, the undisturbed and disturbed shear strength of sensitive glaciomarine clay at Mink Creek in Northwestern British Columbia were measured at 46 kPa and 0.65 kPa, respectively. With a sensitivity of more than 70, a vast landslide of 2.5 million m³ occurred in this area and covered 43 ha (Geertsema et al. 2005).

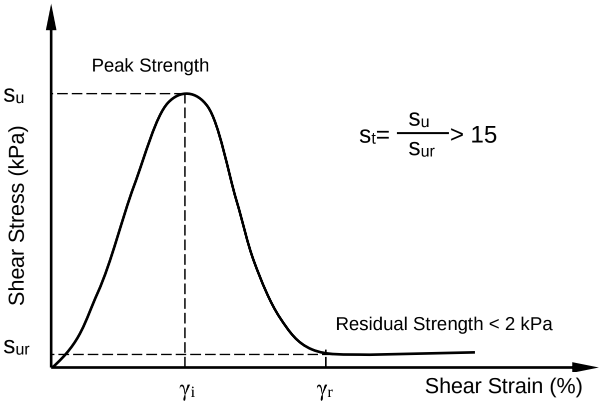

Figure 1: Schematic stress-strain curve for brittle clay and definition of sensitivity

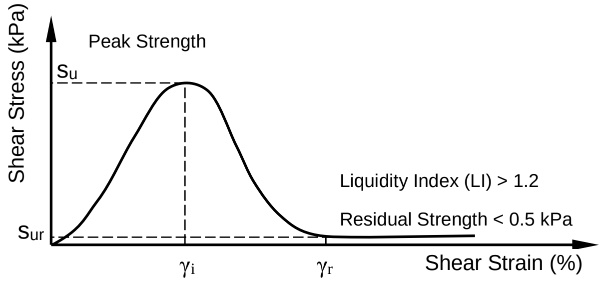

Figure 2: Schematic stress-strain curve for quick clay and definition of sensitivity

Several classification systems have been proposed in literature for sensitivity. Among them, the sensitivity scale proposed by Torrance (1983) that is used by Norsk Geoteknisk Forening, has been used in many geotechnical practices where sensitive clay is a concern. According to this classification, materials with sensitivity of more than 30 are considered highly sensitive clays while materials with sensitivity of less than 8 are low sensitive clays. This classification is presented in Table 1.

Table 1: Classification of sensitivity values for clay (Norsk Geoteknisk Forening, 1974 in Tan et al. 2006)

Classification	Sensitivity Value
Low Sensitivity	<8
Medium Sensitivity	8 – 30
High Sensitivity	> 30

Based on The Norwegian Water Resources and Energy Directorate (NVE), clays with a sensitivity of more than 15 and remolded shear strength of less than 2.0 kPa area are treated as brittle clay. Brittle clay can be divided into two subcategories: quick clay with remolded shear strength of less than 0.5 kPa and sensitive clay as shown in Figure 1. Based on tests conducted (Figure 4) on a quick clay before and after disturbance, shear strength dropped from approximately 100 kPa to about 0.05 kPa by adding 1% by weight of sodium metaphosphate, which affects inter-particle forces. Quick clay can be found in many areas in northern countries including coastal areas of the St. Lawrence Basin, the Hudson Bay Lowlands, Quebec, and near Terrace, British Columbia in Canada; the St. Lawrence Basin and Alaska in the USA; Norway, Sweden, and Finland; and Ariake Bay in Japan.

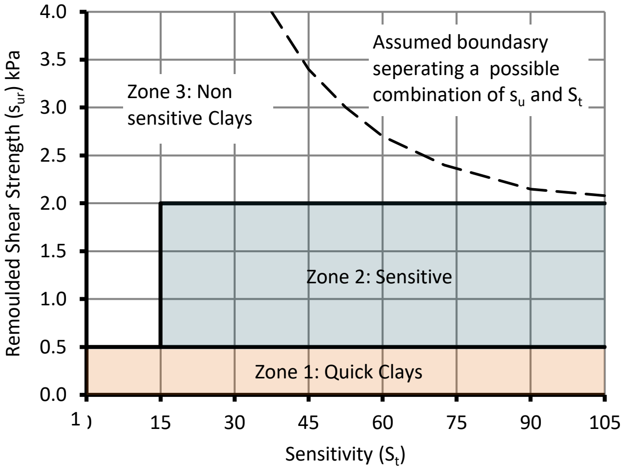

Figure 3: Classification of brittle clay based on sensitivity and remolded shear strength (redrawn from Thakur et al. 2012)

Quick clays also have a high liquidity index (LL) of more than 1.2. This index can be calculated as a ratio of the difference between the natural water content (W) and the plastic limit (PL) to the difference between the liquid limit (LL) and the plastic limit:

$$LI = \frac{W - PL}{LL - PL} \qquad [2]$$

It should be noted that having a liquid index higher than one means the water content of clay is more than its liquid limit and it is highly susceptible to liquefy.

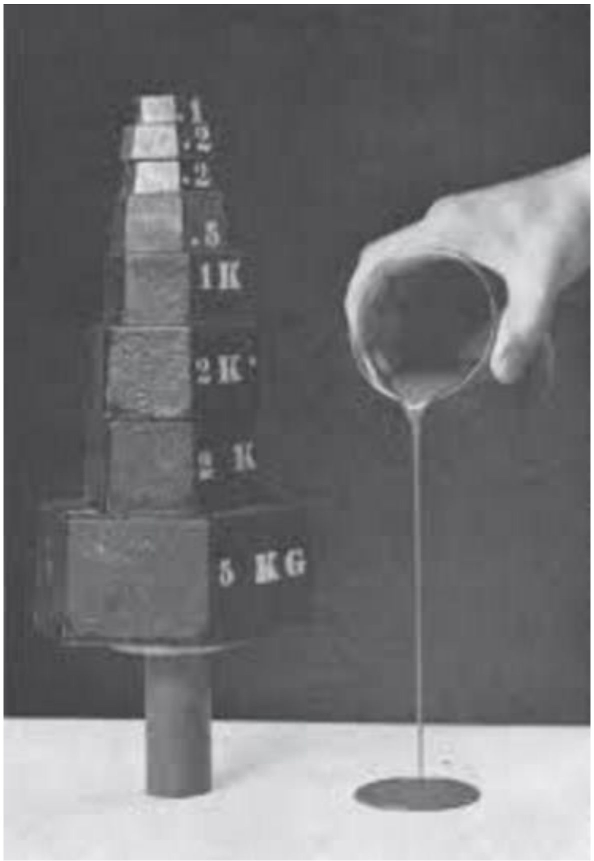

Figure 4: Demonstration of undisturbed and disturbed shear strength of quick clay (Crawford 1963)

4 LANDSLIDES IN SENSITIVE GLACIOMARINE CLAY

A number of catastrophic landslides have been reported in sensitive glaciomarine clay deposits in Scandinavia and northern North America. A vast landslide in these deposits may occur if slide debris remold completely and are also able to flow out of the slide area when they become remolded. A typical flow slide in sensitive glaciomarine clay has certain characteristics which make it an easily recognized earth feature to identify. In general, landslides in these materials have a bottle-neck-shaped opening and flow down valleys (Figure 5). According to Cruden and Varnes (1996) landslide classification, these landslides are classified as flows or spread. The final failure surface in these landslides is not perfectly circular and has multiple composite failure zones.

For stability analysis, Morgenstern and Price (1965) found that these two types of slides can be differentiated using the degree and form of disturbance on the sliding surface (Mitchell and Markell 1974). Depending on the thickness of sensitive clay, regional topography, clay characteristics, etc., the size and shape of landslides vary. Evidences from occurred landslides in Norway show they have hundreds of meters length with a length to height ratio

(L/H) up to 90 (Mitchell and Markell 1974). However, smaller length to height ratios have been reported for landslides occurring in BC (Geertsema et al. 2006).

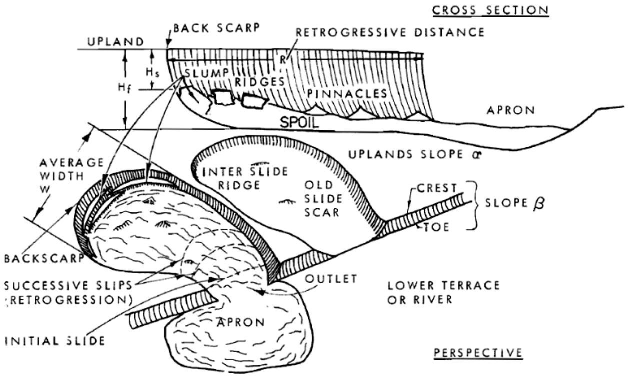

Figure 5: A schematic earthflow and its typical features (Mitchell and Markell 1974)

As shown in Figure 6, an initial slide occurs under a long term drained condition and may be prevented by initial slope stabilization techniques such as re-sloping or slope drainage. Once the initial slide occurrs, the retrogressive sliding progresses under an undrained short term condition and may extend to a distance of fifteen times the height of the slope beyond its toe (Havnen et al. 2017). Based on conducted finite element studies of stresses in slopes, it can be concluded that a horizontal distance between 3H.secβ and 4H.secβ (H is slope height and β is slope angle) beyond the toe of the slope may be considered for the initial failure (long term drained condition). Consequently, any retrogression would occur beyond this limit as a short term undrained condition (Mitchell and Markell 1974).

In general, the areas covered with sensitive clays with slope (β) steeper than 1:15 (about 3.8°) and terrain height (H) more than 10 m that extended to more than 15H from the bottom of the slope should be considered as potential landslide hazards for pipeline routing (Kalsnes et al. 2017).

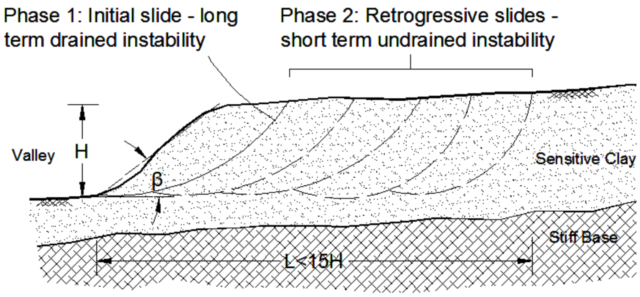

Figure 6: Retrogressive development of a landslide in sensitive clay

Landslides in sensitive glaciomarine clays usually occur very quickly. Based on landslide velocity classifications presented by Varnes (1978), later modified by Cruden and Varnes (1996), these landslides are categorized in classes 6 and 7 (Table 2) as very rapid to extremely rapid landslides and have a velocity of few kilometers per hour. The velocity of the Rissa landslide was initially about 10–20 km/h, and then increased to 30–40 km/h (L'Heureux et al. 2011).

Table 2: Landslide velocity classifications (Cruden and Varnes 1996)

Class	Description	Speed	
7	Extremely Rapid		
		5 m/s	5×10³ mm/s
6	Very Rapid		
		3 m/min	50 mm/s
5	Rapid		
		1.8m/hour	0.5 mm/s
4	Moderate		
		13 m/month	5×10⁻³ mm/s
3	Slow		
		1.6 m/year	50×10⁻⁶ mm/s
2	Very Slow		
		16mm/year	0.5×10⁻⁶ mm/s
1	Extremely Slow		

A sequential retreat of the backscarp rupture mode known as the retrogressive mechanism is common in landslides occurring in sensitive glaciomarine clay. The progressive failure in this material begins when local shear stresses increase due to natural events, such as stream bank erosion, or by human events, such as fill placement, and exceed the peak shear strength of soil. The failure plane advancement is accompanied by sufficient differential strain, causing failure within the clay. Since the remolded (post-failure) shear strength is considerably low, stress concentration zone move into the intact clay. This progressive failure continues and reaches a separation surface such as ground surface, tension crack, etc. and the entire clay mass flows out into a valley. During the progressive failure, the deformation associated with failure collapses microstructures in sensitive clay and generates positive pore water pressure that facilitates undrained failure. In conclusion, a slide in sensitive glaciomarine clay deposits may be triggered by movement or unloading at the toe of the slope, loading at the top of the slope (static condition), or earthquake loads (dynamic condition). Riverbank erosion is considered the most common cause to initiate a landslide in these materials.

5 GEOPROCESSING MODEL FOR LANDSLIDE MAPPING

A Geoprocessing Model was developed in GIS to analyze relevant spatial data and generate the desired outputs for landslide mapping. The data is comprised of surficial terrain polygons interpreted from stereo orthophotos and a LiDAR Bare Earth Digital Elevation Model (DEM). The model first processed the LiDAR DEM to isolate ground surface locations overlapped by polygons in the surficial terrain mapping identified as having clay materials present in either a surficial or sub-surficial state. The DEM was then converted to a slope raster to identify the gradient of each cell within the LiDAR surface. The slope raster was then filtered for evenly sloping terrain with an inclination greater than 1:15 (Havnen et al. 2017). The resulting raster identifies the initial failure zones (Phase 1) within locations where clay material is present. The elevation difference between the toe and crest of each failure zone was then calculated to derive the height of the zone (value ‘H’ from Figure 6). The potential areas impacted by retrogressive land sliding are then identified by buffering the toe of each region for a length (L) equal to 15H (or Phase 1 + Phase 2 in Figure 6). Areas within the potential impacted area that have a lower elevation than the zones toe have been excluded. The general logic used is shown in Figure 7.

6 ANALYZING GEOPROCESSING RESULTS

The results of the geoprocessing model were layered onto topographical mapping to produce a visualization that can subsequently be used in the engineering design of a pipeline system. In areas where pipeline routing does not have significant constraints, the potential impact zones should be avoided by routing and construction activities. When routing is constrained for various reasons and the impact zones cannot be avoided, the initial failure zones (Phase 1) should be avoided as much as possible and mitigations should be taken to limit risks associated with regressive landslides. The quality of the model results is dependent of the quality and resolution of the input source data. In order to accurately evaluate localized ground slope, a DEM derived from the bare earth classifications of a LiDAR point cloud are recommended. Terrain mapping that can identify surficial and sub-surficial materials is also recommended.

For a pipeline project in northern BC, two areas were identified in the preliminary desktop studies. In these two areas, clayey units with topographical criteria discussed in the previous sections were identified along the pipeline route. The geology map of one of the areas with glaciomarine clay is shown in Figure 8.

Figure 9 shows geoprocessing analysis results conducted on the areas shown in Figure 8, where glaciomarine clay was identified in surficial geology maps. According to the digital elevation model provided for this location, the area is about 550 acres with a length of about 2.25 km. Maximum and minimum elevations of the area are 1.8 m.a.s.l. and 201.6 m.a.s.l., respectively, with a general slope of 14.3°.

7 MITIGATION METHODS AND RISK ASSESSMENT OF LANDSLIDES IN SENSITIVE CLAY

In general, landslide mitigation means implementing activities to reduce and possibly prevent the adverse consequences of ground movement. For early stages of pipeline routing, the most recommended strategy to mitigate landslides effects on pipeline integrity is avoidance of the areas and consideration of alternate routes for the pipeline. However, where re-routing is not possible, a comprehensive risk mitigation program should be considered including landslide occurrence possibility, failure consequences, instrumentation and monitoring and, possibly, landslide stabilization. Kalsnes et al. (2017) proposed a hazard scoring table as presented in Table 2. According to the scores presented in this table, landslide hazards are divided into three classes: high hazard when the hazard score is between 26 and 51, middle hazard when the hazard score is between 18 and 25, when there exists a higher, though not critical, probability of sliding, and low hazard when the hazard score is between 0 and 17. Considering the consequence classes provided in Table 3, the risk value can be calculated as:

$$\text{Risk} = \text{Hazard} \times \text{Consequence} \qquad [3]$$

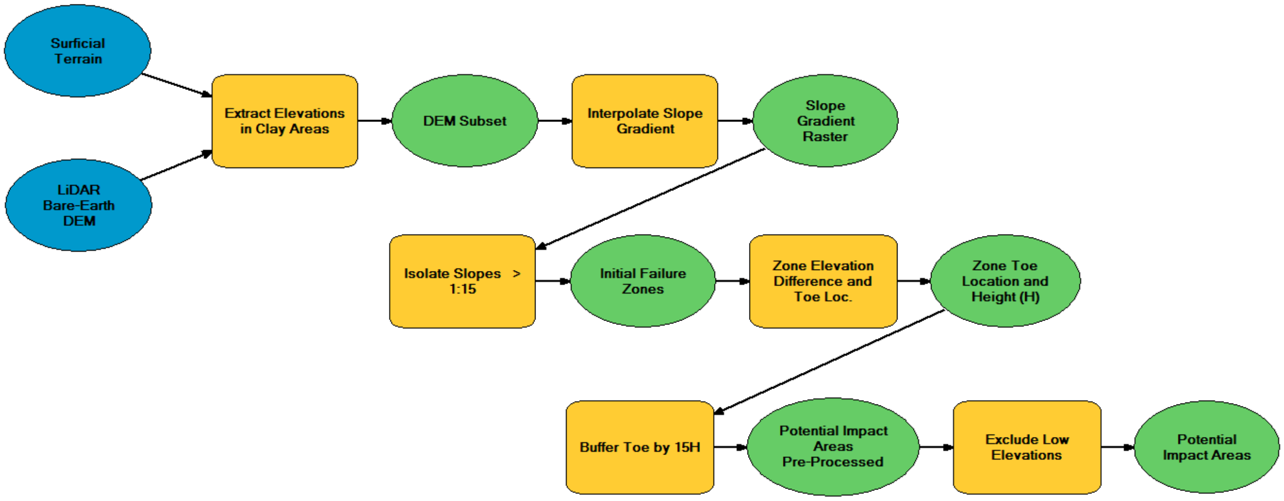

Figure 7: Geoprocessing Model to identify areas of potential retrogressive landslide hazards

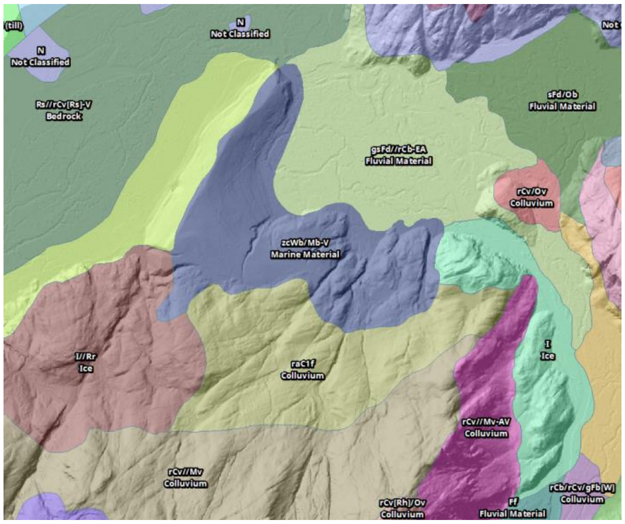

Figure 8: Geological map for the area with potential regressive landslides

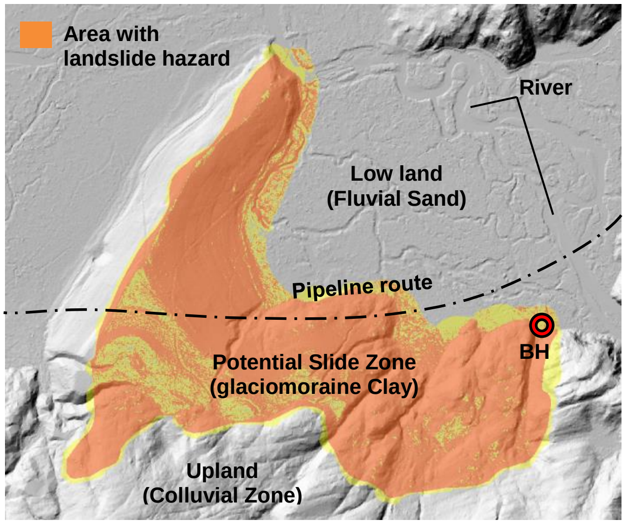

Figure 9: Mapping Areas of Potential Regressive Landslides

For the two areas identified along the pipeline route, landslides fall within the middle hazard zone (hazard score between 18 and 26), while the consequence score is low, as both areas are remote with no human life threat. The landslides were categorized as risk class 2, where no additional activity is required. However, it should be noted that the activity matrix proposed by Kalsnes et al. (2017) may be revised according to project specifications.

In one of the areas identified previously, one geotechnical borehole was drilled to a depth of more than 90 meters to access subsurface ground conditions for a river crossing. According to the geotechnical laboratory test, the liquidity index of a clayey unit with a thickness of more than 7 m is about 1.35. The area was considered as a potential zone for a quick clay landslide and a new route was recommended for the pipeline.

Landslides can be stabilized by ground improvement techniques that are mostly considered where re-routing is not possible when landslide occurrence is high and consequences are considerable (high risk), affecting pipeline integrity. However, it should be noted that a significant investment in site investigation and monitoring is needed for hazardous areas.

Most landslides occurring in sensitive clays start with an initial and relatively small scale slide under a long term drained condition and expand backward under a short term undrained condition. As a result, if the initial slide is prevented by slope stabilization techniques such as re-sloping or slope drainage, the whole area will remain stable.

However, when a sensitive clayey soil is about to liquefy, other techniques should be considered to stabilize the ground. One technique that has been studied and used to improve geotechnical properties of highly sensitive glaciomarine clays is treating the soil with salt (potassium chloride). Recent research (Helle et al. 2016) has shown significant improvement in the undrained shear strength and also the pre-consolidation pressure of sensitive clays when salt is added to the soil. In one case, after about 30 to 40 years of salt treatment, the liquidity index still remained below unity and soil did not behave as quick clay.

8 CONCLUSION

An important and crucial analyzing procedure has been presented for pipeline routing through areas consisting of sensitive clays. In this procedure, the areas with potential flow slides can be identified based on preliminary geological-geotechnical information and LiDAR-based digital elevation models. The geomorphological criteria to identify these areas have been provided based on available historical data and previous research.

A geospatial data geoprocessing algorithm has been presented within GIS to map susceptible areas using LiDAR. The introduced geoprocessing algorithm screens the areas with potential landslide hazards based on available geotechnical and geological information. The provided screening tool refines both the mapping and the assessment of risks associated with landslides in sensitive clays.

Methods of mitigation for pipeline routing have also been briefly discussed in this paper. The most secure method to mitigate adverse results of landslides in sensitive clay is avoidance of the areas and re-routing of the pipeline. Other mitigation methods are costly and require more geotechnical information that should be completed if re-routing is not possible.

9 ACKNOWLEDGEMENT

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Table 3: Evaluation of hazard score for slides in quick clay proposed by Kalsnes et al. (2017)

Hazard	Weight	Hazard Score			
		3	2	1	0
Topography					
Earlier Sliding	1	Frequent	Some	Few	None
Height of Slope, H	2	>30 m	20 to 30 m	15 to 20 m	< 15 m
Geotechnical Characteristics					
Over-Consolidation Ratio (OCR)	2	1.0 to 1.2	1.2 to 1.5	1.5 to 2.0	> 2.0
Pore pressures					
In Excess (kPa)	3	> +30	10 to 30	0 to 10	Hydrostatic
Under Pressure (kPa)	-3	> -50	-50 to -20	-20 to 0	Hydrostatic
Thickness of Quick Clay Layer	2	> H/2	H/2 to H/4	< H/4	Thin Layer (~1m)
Sensitivity, S_t	1	> 100	30 to 100	20 to 30	< 20
New Conditions					
Erosion	3	Active/sliding	Some	Little	None
Human Activity					
Worsening Effect	3	Important	Some	Little	None
Improving Effect	-3	Important	Some	Little	None
Total score		51	34	17	0

Table 4: Evaluation of consequence score for slides in quick clay proposed by Kalsnes et al. (2017)

Possible Damage	Weight	Consequence Score			
		3	2	1	0
Human life and health					
Number of dwellings	4	>5 Closely spaced	>5 Widely spaced	≤5 Widely spaced	0
Persons, industry building	3	> 50	10 to 50	< 10	0
Infrastructure					
Roads (traffic density)	2	High	Medium	Low	None
Railways (importance)	2	Main	Required	Level	None
Power lines	1	Main	Regional	Distribution Network	Local
Property					
Buildings, value	1	High	Significant	Limited	0
Consequence of flooding	2	Critical	Medium	Small	None
Total score		45	30	15	None

Table 5: Risk evaluation and activity matrix or slides in quick clay proposed by Kalsnes et al. (2017)

Activity	Risk Class				
	1	2	3	4	5
	0-160	167-600	628-1,900	1,906-3,200	3,200-10,000
Soil Investigations	None	None	Consider additional in situ tests and pore pressure monitoring	Require additional in situ tests and pore pressure monitoring	Require additional in situ tests, pore pressure monitoring and lab tests
Stability Analyses	None	None	None	Consider doing	Require
Remediation	None	None	None	Consider doing	Require

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