Unconventional Clay Landslides in Northern British Columbia, Canada

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ABSTRACT: This paper discusses landslide occurrences in clayey soil deposits in fjords and coastal inlets in northern British Columbia, Canada, which are considered to be of glacio-marine origin and comprised of sensitive clay soils. Recent review of the area in detail has indicated that the mechanism of a "card house" structure failure of the glacio-marine clay in northern British Columbia does not adequately explain the performance of the clay in initiating the landslide events. This paper presents alternative hypotheses of clay performance in an attempt to explain landslide variability in the area and possible clay performance and landslide failure mechanisms.

1 INTRODUCTION

Clayey soil deposits in fjords and coastal inlets in northern British Columbia, Canada have experienced landslides over the past 50 years. Little information had been assembled on the soils of the area, in particular the clays, and only limited investigations and testing had been carried out.

Limited geotechnical investigations carried out have confirmed the presence of sensitive marine sediments in the region. The types of landslides that have occurred are similar to those which frequently occur in the Leda clays of Quebec and of the quick clays in Norway. Recent investigations indicate that the Quebec/Norway model does not adequately explain the landslides in this area of BC.

This paper outlines the geotechnical properties of the clays and proposes an alternative mechanism to explain the slope instability in the region.

2 STUDY AREA

The study area is located in the northeastern part of BC as shown in Fig. 1. Development in the area is limited and a few regional towns exist of which Terrace and Kitimat are the most populous.

The valley between Terrace and Kitimat was deglaciated at the end of the Pleistocene era from about 13,000 to 10,000 years ago. The distribution of marine clayey silt and raised deltaic deposits indicates that glacier retreat was not uniform. Rather, intervals of rapid glacial retreat were separated by periods during which the glacier front was relatively stable. Glacier thinning and retreat was accompanied and followed by rapid glacio-isostatic uplift. As a result of rebound, shorelines fell from about 200 m above sea level 12,000 year ago to the present sea level about 9,000 years ago. It is estimated that about half of the rebound occurred in perhaps as little as 500 years (Fig. 2).

Fig. 1 Study Area

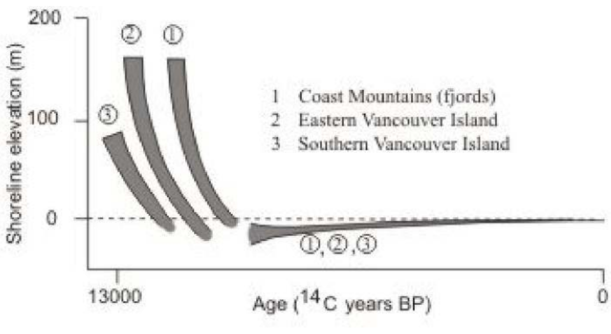

Fig. 2 Relative Sea-Level Change Over the Past 13,000 Years on the British Columbia Coast

Unconsolidated sediments in the valley between Terrace and Kitimat were deposited on isostatically depressed crust at the margin of a retreating tidewater glacier. The dominant sediments are:

- Marine silts and clayey silts, and
- Stratified sands and gravels.

The former are accumulations of glacial rock flour deposited on the seafloor from suspension through the water column and by turbidity currents generated by submarine slope failures. The marine silts contain scattered ice-rafted stones, fossil mollusks, and foraminifera. The sand and gravel deposits are elevated deltas and the braided river floodplains of these deltas.

2.1 *Marine Sediments*

As the sea rose relative to the land some 8,000 years ago (the relative sea-level for the Terrace-Kitimat area is Curve No. 1 on Fig. 2) the Kitimat River laid down a sheet of sand and gravel on eroded fine marine sediments (see Fig. 3). Initially, rapid glacio-isostatic rebound caused the sea to fall sharply relative to the land from about 13,000 to 9,000 years ago. Marine silts were deposited in areas up to 200 m above present sea level during this period. In the early Holocene era, from about 9,000 to 8,000 years ago, the sea was lower relative to the land than today and during this period the Kitimat River built its delta into a lowered sea. As the sea rose relative to the land after 8,000 years ago, a blanket of Kitimat River fluvial sediments was deposited on top of the early Holocene delta plain.

Marine silts are localized south of the two large, valley-wide raised deltas in the valley between Terrace and Kitimat: Marine silts lap up on the gently dipping distal flank (the foreslope) of these two deltas. Silts extend from about 200 m above sea level to well below present sea level. Thick marine silts are extensively gullied, and most of the historic landslides in the valley occur within the areas where the silts are the surface sediments. Marine silts also underlie a sheet of fluvial gravel and sand deposited by the Kitimat River. The river eroded the marine silts during the early Holocene era (i.e. the Holocene era is the past 11,600 years), when the sea was perhaps 10-20 m lower relative to the land than today. Marine sediments are also present on the east and west rock slopes of the Terrace-Kitimat valley, up to about 200m above sea level. They are generally thinner on these slopes than on the floor of the main valley, but they too are subject to landslides. Finally, thick marine silts underlie the seafloor of Kitimat Arm south of Kitimat. They form the surface on which the Kitimat River is building its delta south down the fjord. Fine marine sediments drape the steep walls of the modern fjord.

2.2 *Seismicity*

The National Building Code of Canada prescribes design peak ground accelerations (PGA) of 0.09g and 0.18g for 1/475 and 1/2,475 annual probability of occurrences, respectively, for the Kitimat area.

2.3 *Landslides*

Slope instability in the marine clays is a major concern in the area.

Slope failures can occur on flat slopes due to the sensitive and brittle nature of the clays which can undergo substantial strength loss when subjected to moderate straining. Also thin sand interlayers in the clay may be susceptible to either static or seismic liquefaction, which could have a significant influence on slope stability. Geertsema et al (1997) have documented recorded 'on land' slides throughout the area as shown on Fig. 3. There is also a history of submarine landslides in the northern Kitimat Arm, with several believed to have occurred between 1952 and 1968 and specific events documented in 1971, 1974 and 1975.

3 GEOTECHNICAL ISSUES RELATED TO LANDSLIDES IN SENSITIVE MARINE CLAYS

Geotechnical issues related to landslides that occur in sensitive marine clays are discussed in this section of the paper.

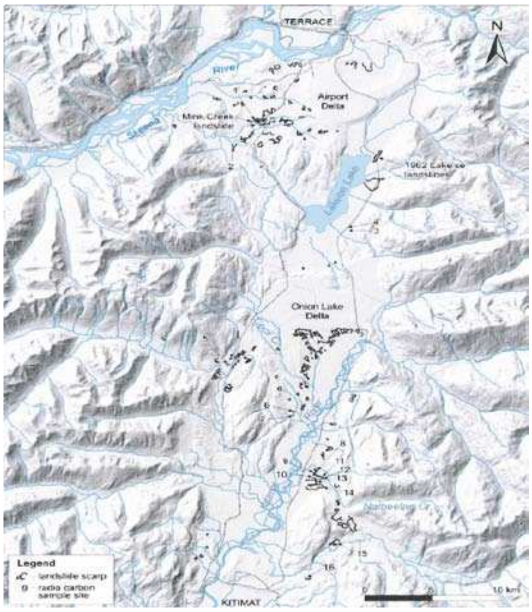

Fig. 3 Documented On-land Slides in the Study Area

3.1 *Glacio-Marine Sediments*

The marine sediments have been deposited, as discussed above, at the front of glaciers and are comprised of clay size 'rock flour' particles. The materials were sedimented in a saline environment and have therefore settled out in a flocculated structure. Because of the saline conditions in which the materials were deposited, the formation of the clays were unique to that environment and have properties different from materials deposited in fresh water such as lake clays. Marine clays are encountered in Eastern Canada, Norway and Sweden and sometimes in other parts of the world including BC.

3.2 Sensitivity

Clay 'Sensitivity'(St) was a term coined by early investigators for the ratio of the undisturbed undrained shear strength of clay to its remolded (disturbed) undrained shear strength. These ratios provide a measure to classify clay considering shear strength and thereby allow assessments of the stability of slopes as a result of disturbance and loss in strength of intact (undisturbed) clay to the remolded value. In highly sensitive clays ("quick" clays), strength loss can be dramatic and extremely large. Clays of low sensitivity are generally in the 1 to 2 range, medium sensitivity are in the 2 to 4 range, moderate sensitivity are in the 4 to 8 range, high sensitivity are in the 8 to 10 range, and quick clays have a sensitivity >10 (sometimes exceeding 100). Several explanations have been postulated for the phenomenon of clay sensitivity as follows:

3.2.1 Load Carrying Soil Skeleton

Casagrande (1932) hypothesized marine clay sensitivity on the basis of a skeleton consisting of silt edge to edge contacts and bond clay creating a matrix of cells in which clay particles are trapped. This type of deposit is created as a consequence of simultaneous deposition of flocculated clay and silt particles in the saline marine environment. The "matrix clay" is prevented from consolidating by the resistance of the contacts of the silt/sand particles. Under high overburden pressures the contact bonds would be expected to be broken and some consolidation to accommodate the effective overburden pressure would occur; however the deposition environment is a continuum and it is expected that clays could vary in the degree of consolidation with depth. The presence of these internal unconsolidated or partially consolidated "cells" would cause excessive water to be released to the soil mass when the bonds of the silt-sized particles are broken under shear, thereby contributing to the sensitive nature of marine clay.

2.3.1 *Cemented Soil Structure*

Winterkorn et al (1947) state that sensitivity results from cementation due to re-crystallization or formation of cementing agents from inorganic substances. Many of the clays have high carbonate contents and high iron contents. Torrance (2013) states that carbonates may not be an effective cementing agent in a water-saturated environment and affirms that iron is a much better agent. The faster cementing occurs in-situ, the more effective is cementing in limiting consolidation. Cemented sediment may develop higher water content than might exist under normally consolidated effective overburden pressure conditions. If when undergoing remolding, the applied pressure is higher than the limit resistance of the structure, the cemented bonds yield and consolidation commences as the structure of the clay collapses and free water becomes available.

3.2.3 Salt Leaching

The marine deposition environment results in saline pore water. If subsequent fresh groundwater flow from adjacent hills develops, the salts within the original saline pore water can be leached out and can result in an unstable brittle structure of the clay. This phenomenon is well documented from laboratory testing carried out in Norway (Bjerrum, 1954) and Canada (Kenney, 1967). Deposition of the clay in a marine environment with a salinity of sea water of the order of 35mg/liters with post deposition fresh water leaching from artesian and surface water has resulted in clays with salt concentration much lower that the deposition environment (frequently much less than 3gm/liter). This reduction in salt content has resulted in a card house structure and created a brittle fragile structure supported by the contact attraction of the individual clay particles. These contact forces are easily broken and result in the availability of unbonded molecular water to the clay mass, causing a major reduction in shear strength ultimately leading to slope failures.

3.3 Slope Instability

The phenomenon of landslides in sensitive clays is well-documented in the literature over the last 60 years or so, and many slope failures have been investigated in detail. These sensitive clay slope failures are somewhat unique as they can occur on extremely flat slopes of the order of a few degrees.

Most of the investigations and studies on these types of failures have been carried out in Scandinavia, Quebec and Ontario on Norwegian and Leda/Champlain Sea clays over the last 50 years. In these areas, where many large regional clay earth flows have occurred in the recent past, it has been shown that the very sensitive clays ("quick clays" – at the high end of the sensitivity scale) typical of these types of failures are due to abrupt brittle loss of shear strength. Initially, the mechanics of such failures were not well-understood as it was apparent that, at many sites, the clays turned into a liquid during slope failure. After the concept of sensitivity became better appreciated, laboratory and field testing were able to show the shear strengths of sensitive clays could drastically reduce when the clay was disturbed.

The documented case histories of the disturbance of failed slopes and landslides seemed to point to a retrogressive type of The accepted failure scenario is successive circular arc failures retrogressing back into the ground until the slope was able to support itself at extremely flat angles; there is even a video of this mechanism during a quick clay failure in Norway.

An alternate method of slope failure has been proposed (Quinn et al, 2007) where the landslides are not retrogressive but rather occur with the development of a complete failure surface before any failure occurs. The scenario for this is that the complete failure surface forms and the clay at any location along this slip surface may be at different strain levels and the failure is the result of a translational, subsidence and disruption of a slow moving monolithic slide mass over a developing zone of liquefied clay. Under this scenario, the straining of a slope with shear strength reduction can occur very slowly over geological time and this might explain the unpredictability of such landslides.

The following discussion relates to what is believed to be a better appreciation of the properties of the clayey soils in the Kitimat area

4 OVERVIEW OF LOCAL GEOTECHNICAL DATA

The available geotechnical data in the area is limited due to the remoteness and undeveloped nature of the Skeena/Kitimat valley. However, there seems to be a trend towards Low Plasticity clay with a corresponding low clay mineral content (with less than 40 to 50% clay) and generally only low to medium sensitivity. This would suggest that, in general, the Skeena/Kitimat materials are quite silty and markedly different to the Norwegian and Leda/Champlain Sea clays (where Liquidity Indices are high, clay contents are high, and with corresponding high sensitivities). The salinity values of tested clays in the Skeena/Kitimat valley suggest low porewater salinities, and therefore the material should be quite sensitive according to the 'leached' clay theory. But, this expectation of sensitivity because of low porewater salinity does not seem to be borne out by the limited test results, which is consistent with the low clay content of the Skeena/Kitimat soils.

In dealing with loose silts and clays, the excess pore pressure induced (and measured) by the CPT is especially interesting as this pore pressure is both sensitive to the soil conditions and the overconsolidation ratio (OCR) of the soil. From the current perspective, a study by Konrad & Law (1987) is relevant as it considers the very sensitive eastern Canadian clays that are viewed as a potential analogue to the conditions across the study site. The table below summarizes the properties of the clays at the sites tested by Konrad & Law while Fig. 4 presents their derived relationship between the normalized excess pore water pressure (Bq) in the CPT and the over-consolidation of the clay involved.

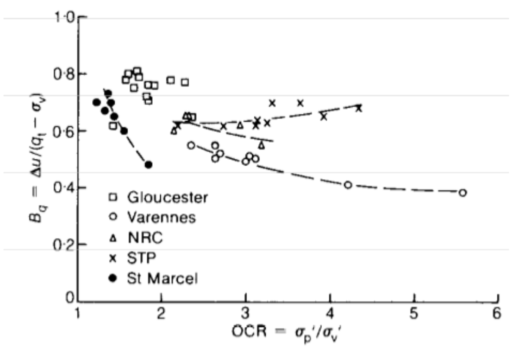

Fig. 4 Bq vs OCR for Sensitive Canadian Clays

Table1. Properties of clays at sites tested by Konrad & Law (1987)

Soil property	Gloucester	St Marcel	Varennes	NRCC	STP
Water content: %	80	80	60	80	70
Plastic limit: %	27	25	22	25	25
Liquid limit: %	55	60	62	60	55
Plasticity index: %	28	35	40	35	30
Clay content: %	80	80	—	70	66
Sensitivity	100	30	20	10–500	40–500
σ_p'/σ_v'	1·5	1·3–1·8	2·4–4·9	1·7–3·7	2·5–4·5
Ground elevation: m	80	—	14	61	53

Fig. 5 shows data from a site in the Kitimat area, processed into the usual dimensionless ratios. In the case of this CPT, two soil units are apparent with the boundary between them at about 14 m depth.

The soil classification plot for the CPT test depth is shown on Fig. 5, and here it can be seen that while the data is mostly in the silty clay range as a 'type' it is in the area of the plot indicating extreme sensitivity. Data in this area of the classification plot are rare, and the reliability of the diagram distinguishing between quick-clays and very-

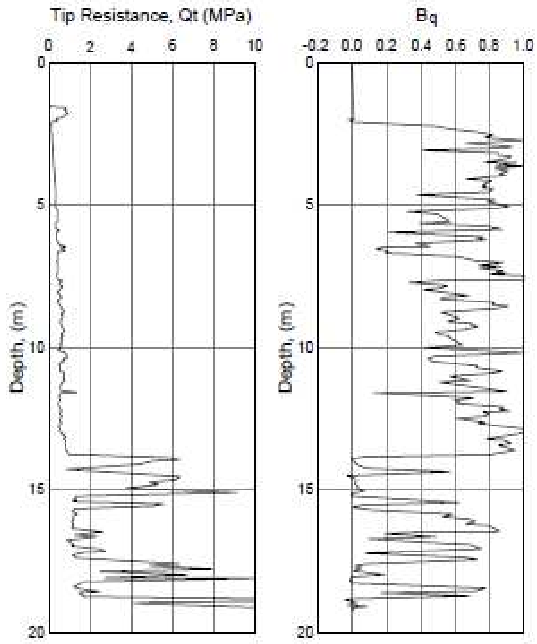

Fig. 5 Typical CPT Data From Kitimat Area

very loose silts is unknown. However, from a practical perspective, both soil types can exhibit substantial loss of undrained strength when strained – the internal mechanics of the material may be different, but the resulting stress-strain behaviour is broadly similar.

Restricting attention to the upper unit, although much of the stratum has a pore pressure ratio Bq ~ 0.6 (which is what we might expect with normally consolidated soils), there is a substantial fraction with Bq > 0.8 indicating soils markedly looser than a normally consolidated condition. A Bq > 0.8 does not imply silt or clay in itself; very loose silts exhibit this magnitude of excess pore pressure as do quick clays (see Fig. 5 and Table 1).

5 CONCLUSIONS

- The soil conditions throughout the Kitimat *Valley extending from Terrace to Kitimat are* complicated and consist of varying thickness of marine Clay of deltaic origin in many cases overlain by alluvial granular strata.
- The marine clays vary in thickness some 8,000 to 10,000 years ago,The clays are of low plasticity and seem to have lower clay contents thanNorway/Canada marine clays.
- The Norway and Canada sensitive clay model for leached marine clays does not provide an accurate indicator of the performance of the Kitimat clays.

  It is postulated that the variation in the clay performance is due to the siltier nature of the strata and the structure of the clay.
- The retrogressive slope failure model is believed not to be a practical mechanism of failure for flat slopes in the area.
- The failure mechanism is postulated to be the development of a complete failure surface which exists before rupture.
- Cone Penetration Testing (CPT) is considered to be the most useful tool in identifying the presence of such clayey soils.

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