SUBMARINE FAILURES IN THE STRAIT OF GEORGIA, BRITISH COLUMBIA: LANDSLIDES OF THE 1946 VANCOUVER ISLAND EARTHQUAKE.

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ABSTRACT
British Columbia hosts Canada's most rapidly developing coastal communities along the semi-enclosed waterways of the Strait of Georgia. This region also is Canada's most seismically active zone. In 1946, the Vancouver Island M7.3 earthquake caused a number of submarine failures of sand and gravel shoreline deposits, destroying coastal facilities, shearing submarine cables and causing large waves. Multibeam and sidescan sonar has been used to map out three submarine landslides, at Goose Spit, Mapleguard Spit and Grief Point. These sites are 32-55 km from the epicentre. The data image the failures in great detail, providing important information on size and style of mass-wasting. The total combined area affected by these three failures is over 1.3 x 10^6 m^2. Submarine cores show the failures consisted of well-rounded beach gravel, cobble and sand, sometimes suspended in a cohesive mud matrix. Cone penetration tests at Goose Spit show soil profiles prone to liquefaction and lateral spreading.

1. INTRODUCTION

Submarine landslides represent a significant hazard to property and life in southwestern British Columbia, since much of the human population inhabits the coasts of the confined marine basins of the Strait of Georgia and Juan de Fuca Strait. The region is seismically active as a result of crustal and subcrustal strain related to convergence and subduction of the Juan de Fuca Plate beneath the North American Plate (Hyndman, 1995, Wang, 2000). In addition, the region was heavily glaciated during the Pleistocene and, in combination with rapid erosion due to the steep onshore topography, thick accumulations of Quaternary and Holocene unlithified sediment lie on local steep gradients. These gradients can be particularly severe on the flanks of the marine basins. Strong tides and currents run through the straits, with tidal ranges of 10 m in places, though more typically 3 m. These tidal fluctuations can cause drastic changes in sediment pore pressures. Furthermore, the tsunamis-generating capability of submarine landslides is high in semi-enclosed marine basins. As a consequence of these circumstances, submarine landslide and associated damage potential is great. In fact, damaging submarine landslides in British Columbia have been observed in recent times related to anthropogenic and natural causes; e.g. Kittimat Arm (Prior et al., 1982). This paper, however, is concerned with three submarine failures that resulted from ground accelerations due to the 1946 Vancouver Island earthquake.

On 23 June, 1946 a magnitude 7.3 earthquake occurred in the central Vancouver Island region (Hodgson, 1946, Rogers and Hasegawa, 1978). The earthquake is believed to have occurred some 30 km in the crust beneath the town of Courtney with either a NW or a NE strike-slip motion. Rogers (1980) documented occurrences of soil failures observed during or immediately following the 1946 Vancouver Island earthquake, as well as from aerial photographic analysis (Mathews, 1979). He included 24 reports of liquefaction, and 17 observations of beach changes and underwater slumping. These failures were observed up to 100 km distant from the epicentre. Three of the observed marine failures are the subject of study in this paper; 1) Mapleguard Spit, 2) Goose Spit, and 3) Grief Point (Fig. 1).

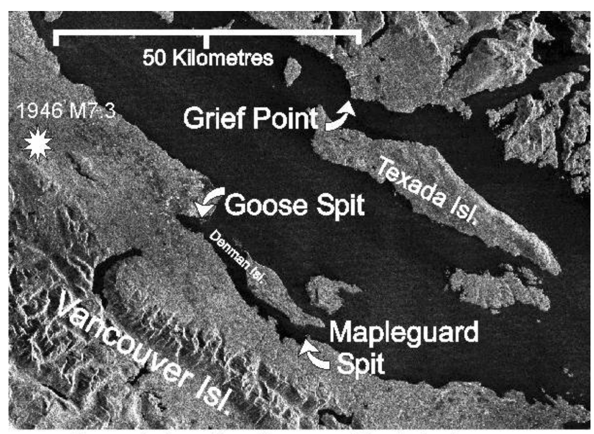

Figure 1. Location diagram of the 3 study areas and the M7.3, 1946 earthquake

It is the purpose of this paper to quantitatively describe the three submarine landslides mentioned above using modern survey and measurement tools in order to understand the processes of submarine landslide failure. In the cases of these failures, the trigger source is relatively well known, the morphology and texture of the failures can be described in detail, and, in one case, the geotechnical properties are well described.

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1.1 Methods

A number of geophysical, geological and geotechnical methods have been used to study the submarine landslides at Mapleguard Spit, Goose Spit, and Grief Point.

Mapleguard Spit and Goose Spit were surveyed in November 1999 with a Krongsberg-Simrad EM-3000 multibeam sonar system operated from the Canadian Coast Guard vessel Revisor. The EM-3000 is a 300 kHz sonar system designed for shallow water hydrographic mapping (< 150 m). It has 127 beams per ping in an angular sector of up to 130 degrees, and can map a swath as wide as 4 times the water depth. The multibeam data were gridded at 1 m for analysis and display. Depth sounding data were used for surface morphology rendering and amplitude backscatter were extracted for sidescan display.

Grief Point was surveyed with a Simrad 992 sidescan sonar operated at 120 kHz. The data were mosaiced and gridded at 1 m to provide complete coverage. These data give an acoustic backscatter image of the seafloor, but no depth data. Grief Point was also surveyed with a Huntec DTS boomer system to collect high resolution seismic reflection subbottom profiles. This boomer has a centre frequency of about 2500 Hz but spans a bandwidth from about 500-6000 Hz, providing vertical resolution of less than 0.5 m.

Nine short sediment cores (<3 m in length) were collected with an Amyers-MacLean vibrocore system. The cores were kept in refrigerated storage until they were split, described and photographed. Cone penetration tests were conducted on Goose Spit in 1990 (Brown and Buck, 1990). These CPT tests included cone bearing, sleeve friction, friction ratio and pore pressure measurements. These data were used in evaluating cyclic liquefaction potential using methods described in Robertson and Wride (1998) and Yoshimine et al. (1999).

2. RESULTS

2.1 Mapleguard Spit

Mapleguard Spit is a gravel/sand, subaerially exposed barrier spit that faces Baynes Channel on one side and Deep Bay on its back-barrier side (Figs. 1 and 2). It is oriented east-west and is about 1 km long. A 1 km-wide intertidal platform flanks the north side of the spit to within 250 m of the west end. About 25 homes are on the spit itself and Deep Bay contains marina and dock facilities.

Mapleguard Spit is 55 km from the epicentre of the 1946 earthquake. Sand boils and liquefaction trenches (lateral spreading) were observed following the event (Hodgson, 1946; Rogers, 1980). The west end of the spit was noted to fail producing a steep embayment at the west tip and north side. The initial retreat is reported to be about 6 m, and the steep initial slopes continued to fail for 3 to 4 weeks. Water depths in this region increased from 0.6 m to 1.5 m to over 30 m during this period. A large wave was generated by this submarine failure, which flipped a boat causing a man to drown; the only death directly related to the 1946 event (Rogers, 1980). Surface renderings of the multibeam data revealed two submarine landslide features on the west-facing, exposed side of the spit (Fig. 2).

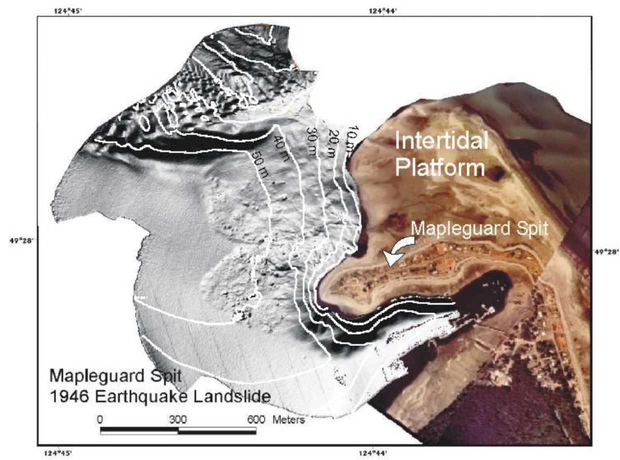

Figure2. Sun-shaded multibeam bathymetry and areal photograph of Mapleguard Spit. Note the two lobes emanating westward from the spit, likely remnant from the 1946 Vancouver Island earthquake. At the north of the multibeam image are sedimentary bedforms in Baynes Channel.

The present-day morphology of Mapleguard spit shows slope angles up to 35° on the upper slope near the low tide water line (Fig. 3). The average slope angle of the spit is about 20° The failure area, presumably resultant from the 1946 earthquake landslide, totals 362,000 m^2 in area. The failure lobes have a blocky morphology, which is somewhat surprising given that the material exposed at the beach is unlithified, well-sorted, grounded gravel. These blocks are up to 4 m in height and 15 m^2 in area. Sediment cores into these blocks show gravel in a stiff clay matrix (Fig. 4). These cores show the failure deposits to consist of well-rounded gravel and sand, with some intervals of gravel and sand in mud. The toe of the landslide lobe is about 0.5 m in height.

2.2 Goose Spit

Goose spit is a sand/gravel, subaerially exposed barrier spit that faces Baynes Channel to the south, and Comox Harbour to the west and east. The town of Comox is north, across the harbour. The spit is 1.6 km long, oriented east-west and connected to the western end of Wilmar Bluffs. An intertidal platform up to 400 m wide flanks the south side of the eastern three quarters of the spit (Fig. 5). The eastern half of the spit is occupied by buildings and facilities of HMCS Quadra (a

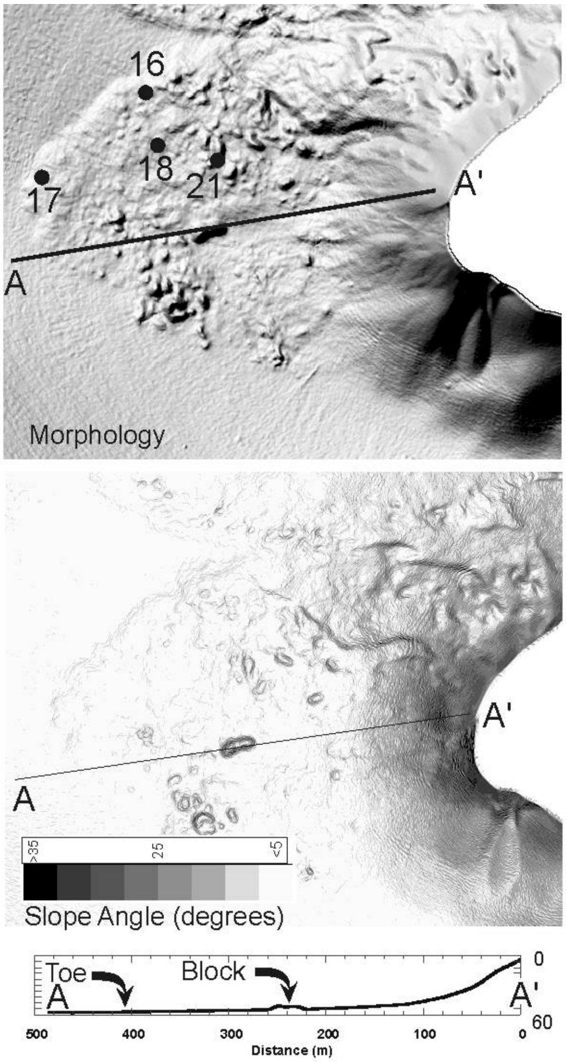

Figure 3. Morphology (top) and slope angle (middle) images and depth profile (bottom) of the southern failure lobe at Mapleguard spit. The profile is at 1:1 scale. Note the blocky morphology of the failure deposit.

naval training base), including a jetty on the north side. The western half is vegetated, uninhabited land and includes property of HMCS Quadra and Indian Reserve Lands. Significant marina and docking facilities exist at Comox.

Medium to coarse sand is exposed at the surface or in shallow excavations on the vegetated parts of Goose Spit. The beach on the south side generally consists of coarse sand and gravel, but changes to medium to coarse sand near the western tip.

Goose Spit is 32 km from the epicentre of the 1946 earthquake. Sand blows and other liquefaction features were observed following the event (Hodgson, 1946, Rogers, 1980). As well, onshore cracks and trenches were developed, the most prominent of which was located near the west end of the spit and was 1 m deep, 5 m wide and 100 m long, oriented NW-SE. It probably represented lateral spreading in response to a large submarine slide that was noted. The aforementioned jetty was thrown out of alignment (and remains so today) and reports suggest a company of soldiers on the parade ground collapsed, unable to sustain an "at ease" position (they have since regained their positions, however!).

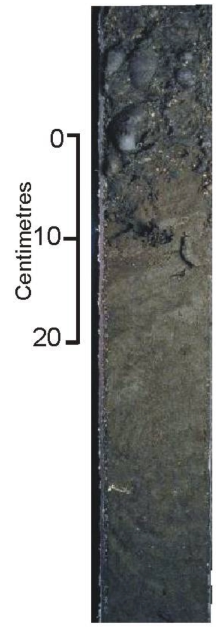

Figure 4. Photograph of lithology of the landslide deposit at Mapleguard Spit (Core16, 20-70 cm), showing coarse gravel in a mud matrix over coarse sand.

Figure 5. Artificial Sun-shaded multibeam bathymetry and airphoto of Goose Spit. The dots represent Cone Penetration Test (CPT) holes, the data of which are used in this study. The area within the broad circular outline is what is believed to be the landslide deposit resulting from the 1946 earthquake.

The present-day morphology of Goose Spit shows that much of the southern face is composed of failure scars

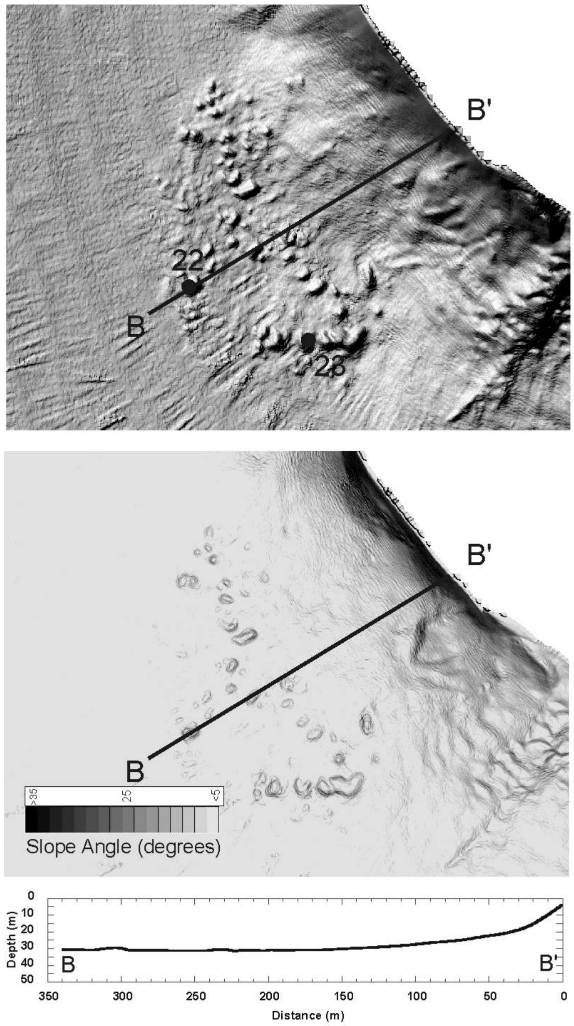

Figure 6. Morphology (top) and slope angle (middle) images and depth profile (bottom) of the failure lobe at Goose Spit. The profile is at 1:1 scale. Note the blocky morphology of the failure deposit. Core positions are labelled with black circles.

and deposits (Fig. 5). The SW tip of the spit is where beach retrogression and failure took place in the 1946 earthquake. The area of the landslide, including the scar and deposit observed on the multibeam data offshore of this point, cover some 83,000 m^2, (Figs. 5 & 6). Slope angles up to 35° on the upper slope near the low tide water line are observed in this location (Fig. 6). Sediment cores into the deposit show gravel in a stiff clay matrix such as observed at Mapleguard. The cores differ, however, in that they show the failure deposits to consist of well-rounded gravel and sand within intervals of fine sand. The toe of the landslide lobe is barely discernible in depth profile and is better demarcated by the limit of the debris blocks.

2.2.1 Cone Penetration Tests

The Geological Survey of Canada sponsored a geotechnical program in 1989 involving four test holes at three sites on Goose Spit (Fig. 5; Table 1; Brown and Buck, 1990). 89-1 was located near the SE-oriented trench at the west end of the spit; 89-3 was located in 8.5 m water depth offshore from 89-1 and above the known 1946 landslide; and 89-2 and 89-4 were located offshore by the mis-aligned jetty on the landward side of the spit. Geotechnical testing included cone penetration tests (CPT and SCPT), standard penetration tests (SPT) and dynamic cone penetration tests (DCPT). Due to space constraints, raw data are not shown.

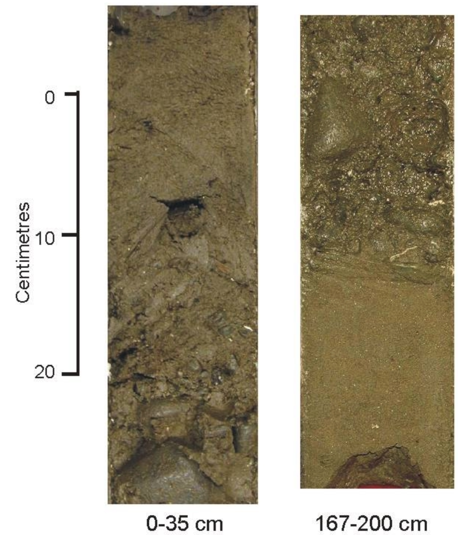

Figure 7 Photographs of Core 23 (see Fig. 6 for location). On the left is the top of the core and on the right is the bottom. These photos show the gravel texture of the landslide deposit and the fine to medium sand texture of the non-failed material. Note the sand over the gravel at the top of the core, representing sedimenation since the 1946 landslide.

Testhole	CPT, SCPT	Borehole with SPT	DCPT
89-1	27.5 m (SCPT)	16.6 m	14.9 m
89-3	15.85 m (CPT)	17.4 m	10 m
89-2	9.6 m (CPT)	8.0 m	
89-4		5.1 m	5.1 m

Table 1: Testhole depths at Goose Spit (after Brown and Buck, 1990).

The geotechnical test hole data show medium to coarse sand with shells and some gravel on the axis and seaward side of the spit, and fine to medium silty sand on the landward side. The top of a dense soil horizon that probably represents overconsolidated Pleistocene deposits dips southward across the spit from –17 to –25 m. Liquefaction analysis of the CPT data were conducted, following procedures of Robertson and Wride (1998) (Fig. 8). CPT data were combined to estimate the cyclic resistance ratio (CRR), which represents the resistance to liquefaction. The strength of the earthquake loading is represented by the cyclic stress ratio (CSR), which is proportional to the peak ground acceleration (PGA). Liquefaction could occur where CSR>CRR. Estimates of the PGA during the

1946 earthquake are between 0.2 and 0.4 g at Goose Spit (Rogers, pers.comm.). Data presented in Figure 8 show that liquefaction is likely at all sites with a PGA 0.3 g. Sites 89-2 and 89-3 are liquefiable with ground accelerations 0.1 g. Using a PGA of 0.3 g, the percentage of liquefiable sand increases from 75% in 89-1, to 90% at 89-2 and 97% at 89-3. Yoshimine et al. (1999) suggested that if the clean sand-equivalent normalized tip resistance (i.e., mean less one standard deviation) is less than 60, the sands are very loose and a liquefaction flow slide is possible. This value is approximately 80 at 89-1, where a flow slide would be unlikely, but it is 51 and 41 at 89-2 and 89-3, respectively. 89-3 is at the head of the identified submarine landslide.

A back-analysis to estimate the PGA experienced during the 1946 earthquake was performed on the CPT at 89-1, which has the highest average tip resistance and CRR. The percentage of liquefiable sand declines from 42% at 0.2g, to 14% at 0.15g, and is 0% at 0.1g. Based on this CPT, the minimum acceleration required to cause liquefaction at this site would be 0.15 to 0.2 g; well in agreement with the actual PGA estimates of the 1946 event.

The higher tip resistance at 89-1 compared to 89-2 may be due, in part, to finer grain sizes at 89-2. This possibility is supported by analysis of the SPT data, which show roughly comparable results for the two test holes (CRR=±0.10 at 5 m). Because the SPT-derived CRR at 89-1 is lower than that derived from the CPT, conclusions based on this CPT may be non-conservative (minimum PGA for liquefaction may be lower than indicated above). Conversely, the SPT-derived CRR at 89-3, where coarse sand was reported, is 50% higher than that derived from the CPT, possibly due in part to the high shell and woody organic content of the sand (Brown and Buck, 1990). The relationship between grain size and tip resistance needs further investigation.

2.3 Grief Point

Grief Point is located on the mainland side of the Strait of Georgia (Malaspina Strait) (Fig. 1), about 56 km from the epicentre of the 1946 earthquake. A submarine landslide was known to have occurred as a result of the earthquake because a telephone cable extending from Grief Point across Malaspina Strait to Vananda on Texada Island was severed. The cable was replaced and the corridor is still active today.

No multibeam data exist at this site, but the area was imaged with sidescan sonar and seismic reflection profiling. A mosaic of the sidescan sonar data (Fig. 9) shows the landslide deposit. A number of downslope trending chutes are apparent and the landslide appears

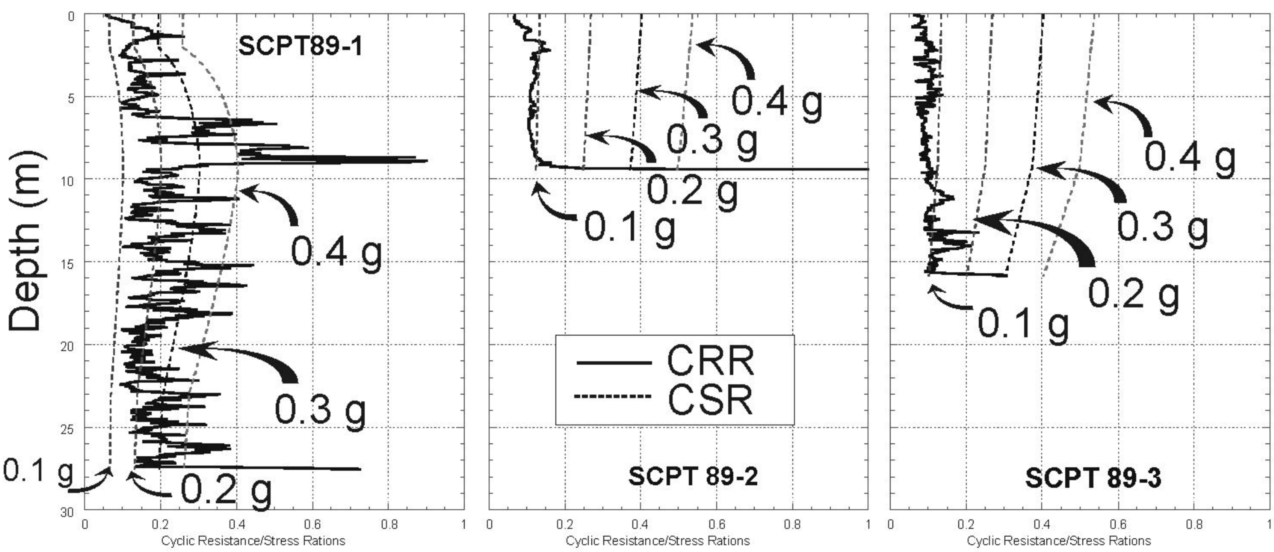

Figure 8. Cyclic resistance ratio (CRR) and cyclic stress ratio (CSR) plots of sites 89-1, 89-2 and 89-3 based on the CPT data. Where CRR values are less than CSR values the Factor of Safety exceeds 1 and liquefaction is likely.

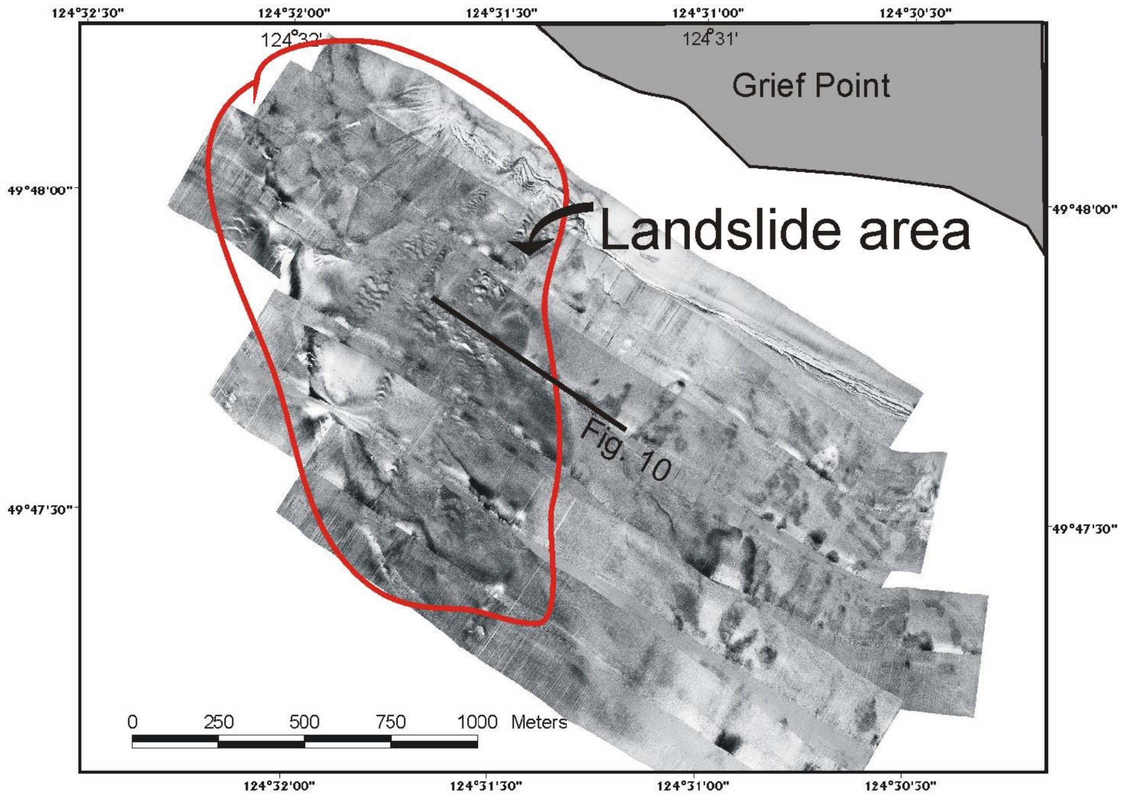

Figure 9. Sidescan sonar mosaic of the Grief Point landslide. Water depths span from 20 m in the north to 220 m in the southwest area of the image. The location of a seismic section (Fig. 10) is shown.

to have occurred in a series of narrow corridors, where you can see sediment-wave-like features. These waves are likely retrogressive failure scars. The failures look much like subaerial landslides of unlithified material on very steep slopes. On the extreme left of the mosaic, there is a trench into which much of the material may have been deposited. The total area affected by the landslide is 937,000 m^2. In seismic reflection profile (Fig. 10), the landslide deposit is marked by a hummocky surface morphology and acoustic transparency, with no internal structure. Very little acoustic penetration is achieved with the Huntec boomer into the surrounding lithology, suggesting it may be bedrock.

Remotely operated vehicle (ROV) video data were collected at the site. The old broken cable was located in some frames. The video also shows that the landslide deposit consists of gravel and small boulders within a mud matrix.

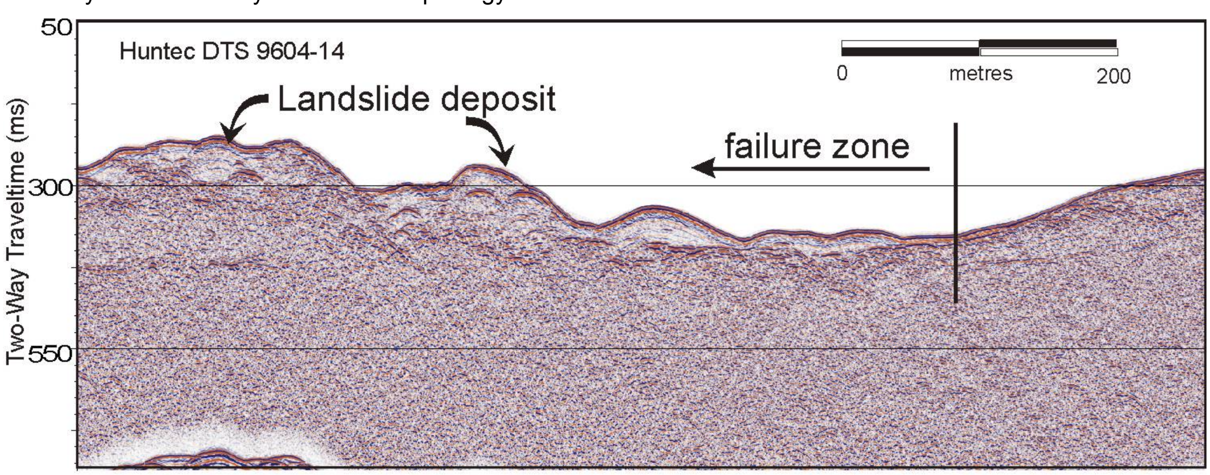

Figure 10. Huntec boomer seismic reflection profile across the Grief Point submarine landslide.

3. SUMMARY

The 1946, M7.3 Vancouver Island earthquake caused numerous occurrences of soil failure, which resulted in landslides where slopes were involved. 17 occurrences of beach retrogression and slope failures were noted in the marine environment (Rogers, 1980). Three of these slope failures are the subject of study in this investigation; Goose Spit near Comox, Mapleguard Spit near Deep Bay, and Grief Point, south of Powell River.

Although only one seismograph recorder was in operation on Vancouver Island in 1946, the earthquake event was well documented (Hodgson, 1946). These data provide control on the characteristics of the earthquake and consequent ground accelerations, which are believed to be between 0.2 and 0.4 g for the sites investigated in this report. Detailed investigations of the morphologies and sediment characteristics of the resultant submarine landslides provides a mechanism with which to study the consequences of ground accelerations and assess the coastal hazards these failures represent.

Multibeam sonar data provide a powerful mechanism to study both visually and quantitatively the morphological characteristics of these submarine landslides. Both the Mapleguard Spit and Goose Spit failures show lobe-shaped deposits and steep (>35°) upper slope failure scars resulting from the landslide. Sidescan sonar of the Grief Point landslide provides textural information and allows delimitation of the landslide, but does not provide the quantitative morphological information. These data show the Grief Point failure to have occurred in several narrow corridors and probably was a much more fluidized flow, given the distance it traveled and the texture of the deposit. The total area affected by all three failures is in excess of 1.3×10^6 m^2.

The surface texture of the Mapleguard and Goose Spit deposits shows blocks several metres in diameter and height. This feature is surprising given that the exposed surfaces of the spits are well-washed sand and gravel. One would expect this material to spread laterally in fluidized flow. Shallow sediment cores in these deposits show well-rounded gravel in a stiff mud matrix, explaining the presence of the blocks. The source of this fine-grained material is not known but most likely the spits are composed internally of overconsolidated silt and clay, and the landslide occurred within or beneath this material, incorporating it with the gravel during failure.

Four geotechnical test holes at three sites, including SPT, CPT and SCPT testing were conducted on Goose Spit. The data from these tests shows high cone bearing strengths at variable depths, suggesting over-consolidated soil, possibly Pleistocene deposits, within the spit. These data support the hypothesis that the spits are composed internally of fine-grained, overconsolidated material and explains the blocky nature of the debris lobes.

In the upper portions of the test holes, bearing strengths are low and liquefaction is probable at all sites with ground accelerations above 0.3 g. The test hole in shallow water (8.5 m) above the landslide deposit (89-3) shows that liquefaction is likely with ground accelerations above 0.1 g. This location juxtaposes a 35° free slope at the face of the spit, thus the likelihood of post-liquefaction flow is very high. Back-calculation to estimate the peak ground acceleration experienced during the 1946 earthquake suggests that a minimum of 0.15 to 0.2 g were required at 89-1 on Goose Spit.

4. CONCLUSIONS

The marine waterways of British Columbia are such that much of the coastline dips from sea level to water in excess of 300 m deep within a very short distance, giving way to steep slope gradients. Locally, there are many instances of thick deposits of unlithified or semi-lithified sediment at the coastline. In addition, strong tidal currents have built many examples of spits and bars, some of which are inhabited. This unlithified sediments, as shown in the 1946 earthquake, can be prone to liquefaction, and those that exist on slopes are highly susceptible to post-liquefaction landsliding.

Slope failure of unlithified sediment in the marine environment can wreak havoc on coastal and underwater structures and cause retrogression of the coastline, as has been shown in the examples in this paper. Failures of semi-consolidated material, such as that which appears to have taken place on Goose Spit and Mapleguard Spit, are particularly hazardous in that they can produce waves or tsunamis, which inundate the coast, causing further, and perhaps more excessive damage. This study shows that submarine landsliding is possible, and even likely in many coastal settings of British Columbia, with even moderately low ground accelerations.

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6. ACKNOWLEDGMENTS

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