LANDSLIDE-GENERATED TSUNAMIS AND THEIR RISK IN COASTAL AREAS

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ABSTRACT
Tsunamis have generally been viewed as being a direct consequence of fault movements in oceanic areas and associated with large earthquakes. In recent years, however, researchers have come to recognize that underwater landslides, or subaerial landslides entering standing bodies of water, whether triggered by an earthquake or not, can give rise to devastating tsunamis impacting coastal areas. In this paper we review three examples of subaqueous and combined subaerial-subaqueous slope failures in southeast Alaska (Skagway) and coastal British Columbia (Kitimat and Knight Inlet) that gave rise to destructive local tsunamis. Anecdotal evidence suggests that these kinds of events are more common than generally reported. Assessment of the risk of landslide-generated tsunamis in high-relief coastal areas should be routinely undertaken during the planning for coastal infrastructure development.

RÉSUMÉ
Les tsunamis ont généralement été perçus comme étant directement reliés aux mouvements de failles dans les régions océaniques et ont été associés aux tremblements de terre. Cependant, les chercheurs ont récemment remarqué que les glissements de terrain sous-marins ou sous-aériens résultant d'un tremblement de terre ou non et pénétrant une masse d'eau, peuvent causer des tsunamis dévastateurs affectant les régions côtières. Dans cet article, nous réviserons trois exemples de glissements de terrain sous-marins et de glissements déclanchés sur terre qui se sont déposés dans un environnement aquatique. Les exemples présentés où les mouvements ont créé de grands tsunamis sont en Alaska, à Skagway et en Colombie-Britannique soient à Kitimat et à l'anse Knight. Des témoignages nous suggèrent que ces types de glissements de terrain sont plus communs que l'on ne puisse croire. Des évaluations de l'état des risques de tsunamis produits par des glissements de terrain dans les régions côtières montagneuses devraient être menées de façon routinière lors de la planification du dévelopement de diverses infrastructures.

1. INTRODUCTION

Traditionally tsunamis have been viewed as mainly the direct consequence of fault movement in deep oceanic areas and associated with large earthquakes. More recently, however, researchers have come to realize that either subaqueous slope failures, or subaerial landslides entering coastal waters, can give rise to devastating tsunamis; these events can occur in the absence of any seismic activity. The most devastating tsunami of the twentieth century (Papua New Guinea, July 17, 1998; Smith 2000) was a consequence of a very large submarine slope failure triggered by a modest earthquake. Similarly, the most catastrophic documented tsunami in Canada (southern Newfoundland, November 1929) in which 27 people were killed, was the result of a moderate earthquake that gave rise to a large slope failure on the continental slope off the Grand Banks. In both of these cases, the tsunami was the result of the downslope movement of landslide masses and not the direct consequence of the earthquakes. In this paper we shall examine the tsunami events at three West Coast sites that resulted from slope failures in fjord settings. We hope to demonstrate that such events are neither rare nor insignificant and their risk should be considered in coastal infrastructure planning.

2. KITIMAT, BRITISH COLUMBIA

The Vancouver Sun reported in April 1975: " A freak wave Sunday caused by an underwater slide roared up Douglas Channel, demolishing docks and swamping boats at Kitimat. It was a big wave, close to 25 feet, and it just ripped stuff up like matchsticks …. A large section of the Northland navigation dock and a new RivTow Straits barge terminal were destroyed. Four barges … were washed ashore along with a number of small boats. Where there used to be a beach, is now a cliff and 50 feet of water."

This subaqueous slope failure occurred in Moon Bay near Kitimat (Figure 1) at 1005 on April 27, 1975 shortly after an extreme low tide (Figure 2). The failure occurred in cohesive muds and resulted in a debris flow with a volume of approximately 55 x 10^6 m^3 that involved an area of 7.5 km^2 and which extended about 5 km down the axis of the fjord in water depths of about 200 m (Figure 3) (Bornhold 1983; Prior et al. 1982; 1984; Johns et al. 1986).

Conditions that led to failure included: steep subaqueous slopes, significant undrained loading resulting from construction activities and rapid tidal drawdown (Johns et al. 1986).

This was the most destructive of several similar events known to have occurred in the region since the 1950's when the town of Kitimat was established. A 75 m x 20 m pile dock disappeared as a result of the failure and wave and much of the coastline around the head of the fjord was inundated. The wave was estimated at 8.2 m high (Murty, 1979) although this analysis was highly simplistic. It was fortunate that the failure occurred at low tide; considerably greater destruction would have ensued had the state of the tide been higher. Estimated damage (in present dollars) was about $1.75 million.

We are presently carrying out a more rigorous modelling exercise to understand better the relationships between this debris flow failure and the resultant tsunami wave characteristics.

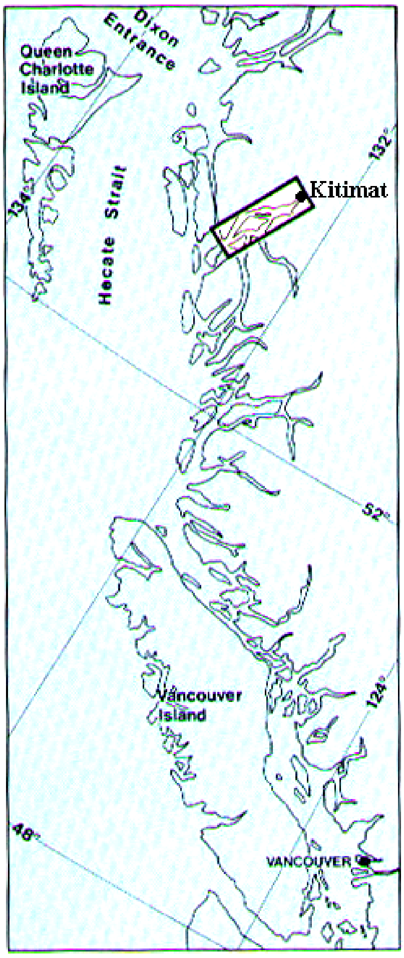

Figure 1. Location map of Douglas Channel and site of Kitimat, British Columbia. (modified from Bornhold 1983).

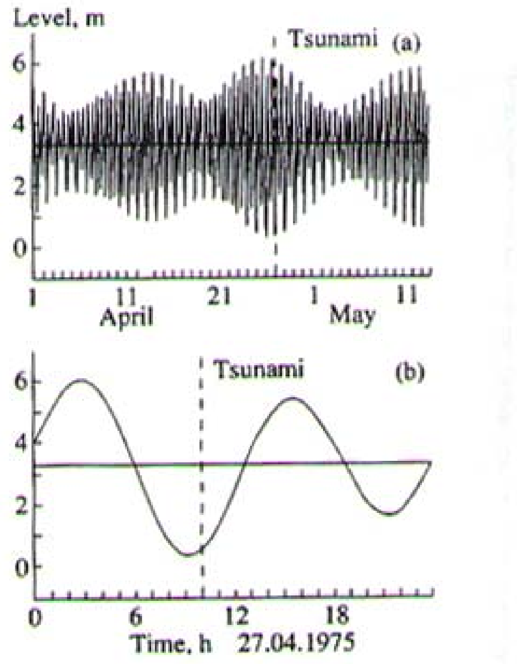

Figure 2. (a) Calculated tides at Kitimat from April1 through May 13, 1975. (b) Part of the calculated tide record from April 27, 1975 showing the moment of slope failure at 1005, just after an extreme low tide (from Kulikov et al. 1998).

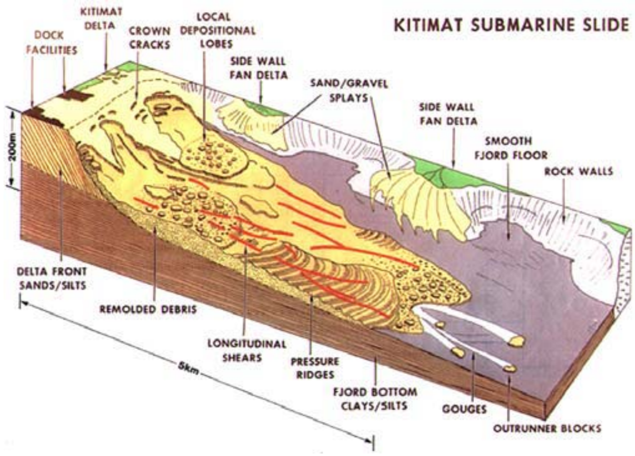

Figure 3. Seafloor morphology of the 1975 debris flow in Kitimat Arm, Douglas Channel that gave rise to the 8-m tsunami. (From Prior et al. 1984)

3. SKAGWAY, ALASKA

At 1912 on November 3, 1994 an underwater landslide occurred beneath the Pacific and Arctic Railway and Navigation dock along the eastern side of Skagway Harbor (Figures 4, 5). Like Kitimat, the failure occurred during construction activities at the site and just after the lowest tide experienced during the construction period (Figure 5). The 300 m long piling supported dock, which had existed for nearly a century, was completely destroyed along with four newly constructed (but unfilled) sheet pile cells that were to form part of a new dock under development (Kulikov et al 1996). The accident killed one worker and resulted in damages to the dock, small boat harbour and Alaska Ferry Terminal initially estimated at about $20 million (Lander 1995); although unpublished, final estimates of damages greatly exceed this early estimate.

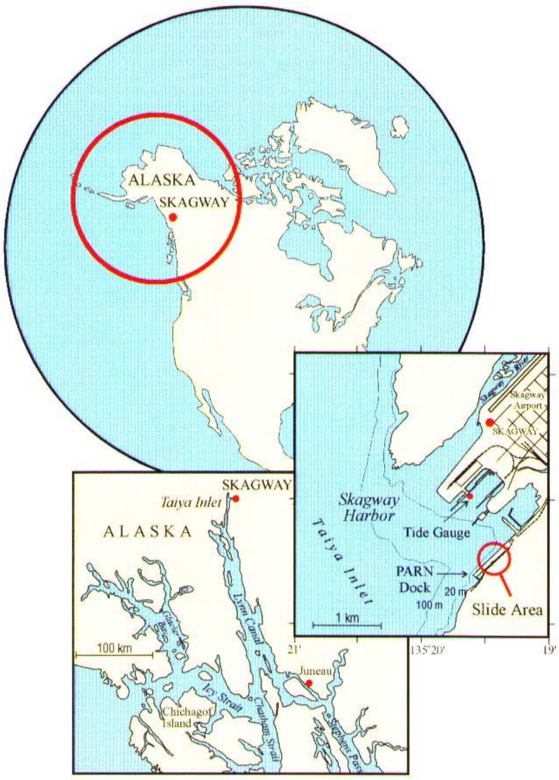

Figure 4. Location map of Skagway Harbor and area of failure.

Unlike Kitimat, the failure was a flow slide consisting of loose silts and sands. These materials had been resting at an angle of repose of 25 to more than 30 degrees on the steep fjord wall slope. A similar failure had occurred nearby in 1966 when fill was being added to the nearshore area.

The failure gave rise to a local tsunami estimated to be between 5 and 6 m high in the harbour and 9 to 11 m high at the shoreline around the harbour (Kulikov et al. 1996). Modelling confirmed the wave period measured by the tide gauge in the harbour of about 3 minutes. The harbour experienced seiche oscillations that lasted for more than one hour as a result of the failure.

As at Kitimat, the failure occurred during construction activities, at an extreme low tide and on steep slopes. Failure conditions were further exacerbated at Skagway by the very soft, non-cohesive sediments along the slope.

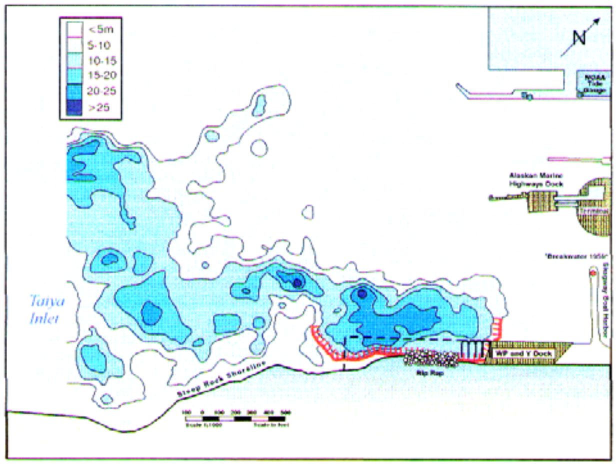

Figure 5. Location and limits of failure in Skagway Harbor. Contours show changes in seafloor pre- and post-failure as a result of the flow slide.

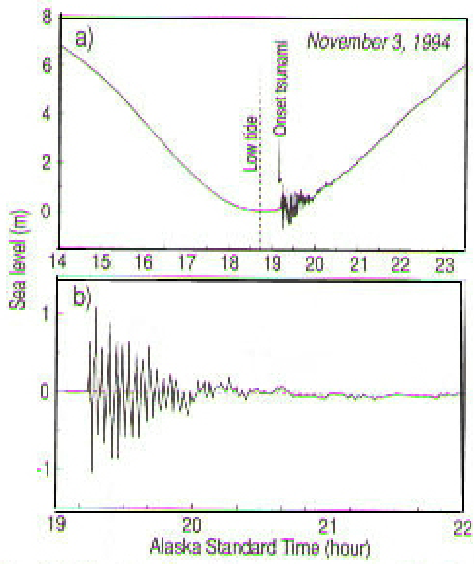

Figure 6. (a) Tide gauge record form Skagway Harbor for the afternoon and evening of November 3, 1994 showing onset of the local tsunami. (b) tsunami record with tidal signal removed. (from Kulikov et al. 1996).

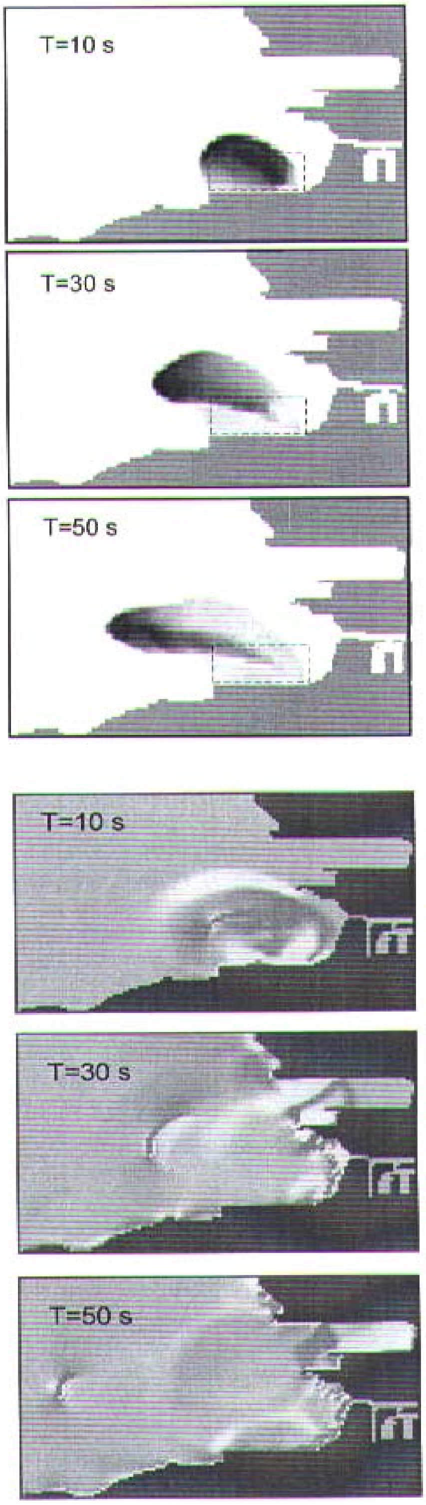

Figure 7. Modelling results for the flow slide in Skagway Harbor at 10, 30 and 50 seconds after the initiation of the failure (top). Modelled tsunami wave (bottom).

4. KWALATE, KNIGHT INLET, BRITISH COLUMBIA

In a recent book by Proctor and Maximchuk (2003) on coastal stories from British Columbia, the following paragraph recounts an apparent landslide-generated tsunami in Knight Inlet that inundated a First Nations village at the mouth of the Kwalate River (Figure 8).

“Kwalate was the site of a big village at one time. The story I was told is that a big part of the mountain across the inlet fell into the sea and created a tidal wave that rolled across the inlet and drowned most of the village.” (Proctor and Maximchuk, 2003; p. 188).

To date we do not know when this event occurred or how many people may have been killed; investigations involving anthropologists and geologists are ongoing. We do know that the site was apparently an important village, marked by nearby petroglyphs and is featured in many stories and legends. It is likely that there were many people in the village at the time; if so, this may prove to be the most devastating tsunami known in Canada.

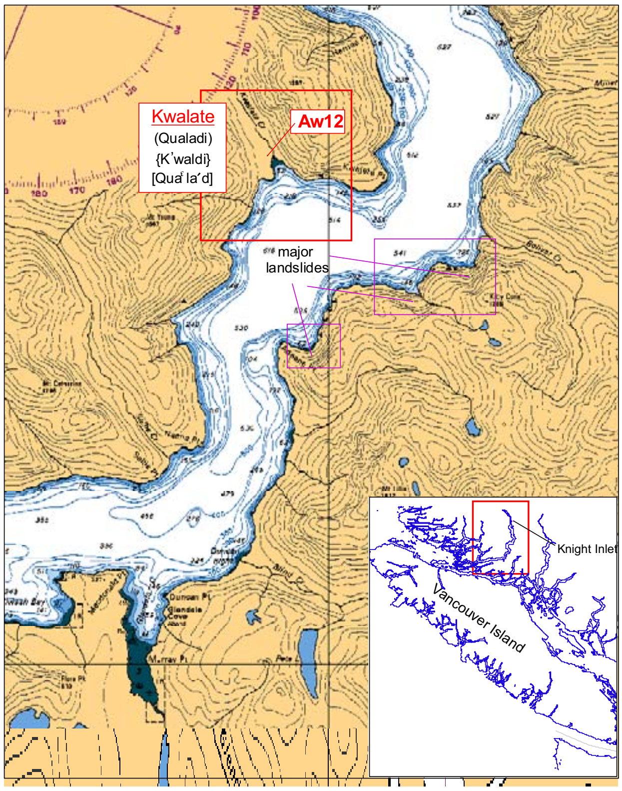

Figure 8. Location map of Kwalate where subaerial rock slides on the mountains opposite the village apparently resulted in a devastating tsunami that destroyed much of the village.

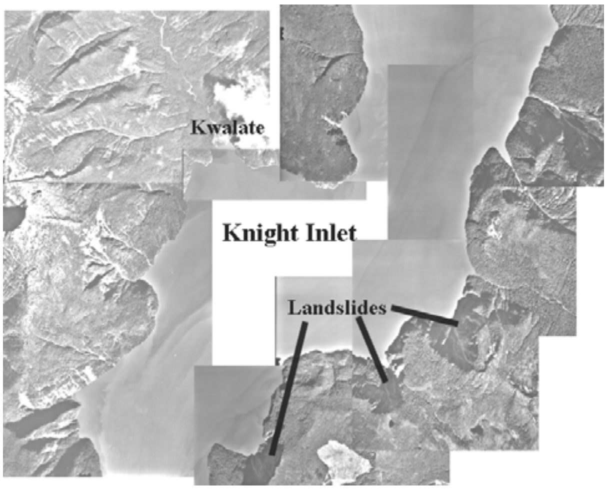

Figure 9. Air photo mosaic of Knight Inlet in the vicinity of Kwalate Point showing the locations of three large landslides. The distance from Kwalate across the inlet is about 5 km.

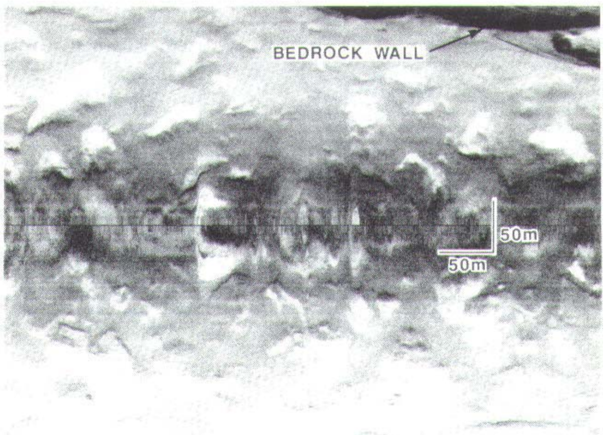

Figure 10. Sidescan sonograph of the east side of Knight Inlet opposite Kwalate Point. Abundant, large bedrock blocks, many greater than 50 m long, can be seen on the fjord basin floor beyond the base of the bedrock fjord wall. (From Bornhold and Prior 1989).

In this instance, the cause of the tsunami was a major subaerial rockwall collapse at one or all three of the landslide sites evident in air photos from the east side of the fjord (Figure 9). Rocky debris from the failure has been found, using sidescan sonar, on the deep floor of the fjord in 540 m water depth (Figure 10). Individual blocks that can be seen rising more than 10 m above the muddy seafloor are up to 40 m long.

This block failure gave rise to a major displacement wave that propagated across and along the fjord. While at present we do not know the amplitude of this wave, we can refer to similar events elsewhere to gain a sense of the possible height. In mid-afternoon, November 21, 2000, a subaerial failure entering the ocean at Paatuut on western Greenland gave rise to a tsunami with a run-up height of 50 m near the failure and 28 m at an abandoned mining town 20 km away. The wave destroyed all but one house in the town; had the event occurred in summer, loss of life would have been serious as the houses are used as summer homes (Dahl-Jensen et al. 2004). From first estimates, the slides in Knight Inlet could be on the same order as the Greenland failure but the Kwalate Village site is only about 5 km away. Further investigations and modelling will attempt to provide a more precise estimate of the wave height.

This type of failure and tsunami is analogous to the famous event in Lituya Bay, Alaska on July 9, 1958 in which part of the rocky mountainside collapsed into the bay and created a tsunami with a documented 525 m run-up (Miller 1960).

5. DISCUSSION AND CONCLUSIONS

Landslide-generated tsunamis in coastal areas of British Columbia and Alaska are known to have caused considerable damage and probably significant loss of life. Because of the remoteness of these areas and the generally low population densities, we do not have a good understanding of the frequency of the events, however. We do know from anecdotal reports and other evidence that there are many more events than are widely documented in the literature. Forestry companies frequently describe failures near log handling facilities (e.g., northern Bute Inlet, British Columbia) destroying new construction and other facilities. Similarly, boating magazines occasionally carry reports of boats being struck by unusual waves in fjords. One recent such article (Mackay and Mackay 2004) reported: " … we woke to a sound that can only be described as a freighter dropping an enormous anchor right over our heads. Almost immediately a huge wave hit us rolling me out of bed." A nearby landslide triggered by torrential rain had entered Codville Lagoon off Fisher Channel on the central British Columbia coast.

Landslide-generated waves are well known in reservoirs and have resulted in extensive damage and loss of life (e.g., Vaiont, Italy). It is inconceivable that a dam project would not include an assessment of the potential for slope failures displacing reservoir waters and, possibly, compromising the integrity of the proposed dam. In the case of coastal development in British Columbia, Alaska or other high-relief areas prone to landslides, however, assessment of the risk from local, landslide-generated tsunamis is virtually never carried out. As more development occurs in such areas, it is recommended that consideration be given to such hazards, originating from both subaerial and subaqueous failures.

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