

Landslide-Induced Wave Hazard Assessment—Tidal Inlet, Glacier Bay National Park, Alaska

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Abstract. An unstable landslide perched above the northern shore of Tidal Inlet has the potential from seismic or climatic trigger of rapidly moving into Tidal Inlet and generating large, long period impulse waves. Numerical simulations of landslide-generated waves indicate that near the mouth of Tidal Inlet, wave amplitude would be greatest within approximately 40 minutes of the slide entering water. Significant wave activity would continue in the western arm of Glacier Bay for more than several hours, while wave amplitudes would decrease in deeper waters. Severity of impact to vessels in the region depends on the size and speed of the slide and on which part of the wave ships would encounter.

Introduction

Glacier Bay National Park is located in a region of high seismicity, which has had four large magnitude ($M > 7.0$) earthquakes during the 20th century (Brew and others, 1995). The 1958 earthquake on the Fairweather fault triggered a 30 million m³ rockslide which generated a 30-m high wave through Lituya Bay sinking two of three fishing boats and killing two persons (Miller, 1960). A large detached rock mass above the northern shore of Tidal Inlet (fig. 1) poses a threat similar to the landslide that occurred at Lituya Bay.

Deglaciation of Tidal Inlet probably proceeded simultaneously with the calving retreat that rapidly depleted ice in both arms of Glacier Bay during the 19th century. Maps by Reid (1896) show that Tidal Inlet was devoid of ice by AD 1890 except for a small remnant glacier at its headwaters. The retreat of glacial ice decreased lateral support for the hillside. Although it is not known exactly when the landslide on the northern shore of Tidal Inlet first moved, the major slide event is evident on photos taken between 1892 and 1919. The general lack of revegetation of landslide features supports minor recent movement of the landslide mass. The objectives of this study are to determine if landslide movement is presently occurring and to estimate wave height and runup from potential landslide impact into Tidal Inlet.

Methods

The main scarp has a fairly uniform range of height, 20–40 m, suggesting that the body of the landslide detached rigidly. Within the main body of the landslide the surface topography is severely disrupted by rotational blocks with



Figure 1. Detached landslide perched above the northern shore of Tidal Inlet, Glacier Bay National Park, Alaska. Photograph taken July 12, 2002.

prominent back-facing scarps. In the upper portion of the main body the exposed portions of these blocks are within glacial till, but further downslope bedrock can be seen within the blocks. The thickness of the landslide was estimated to determine the total volume of material that could enter Tidal Inlet. The stability of the landslide was evaluated by examining the features and by measuring movement of established reference points using GPS. However, on the right (west) flank of the landslide, two closely spaced sets of parallel open fissures were found in surficial soils extending downhill from the termination of the main scarp, and pointing downslope towards the toe of the landslide. These fissures appeared relatively fresh within generally weak soils and would not be preserved for more than a year.

Topographic monuments were installed on the Tidal Inlet landslide to assess movement rates. GPS data were collected for durations of at least one hour and collection intervals

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of 30 seconds at each monument. A base station was set up over a permanent benchmark (CINCO) along the shores of the west arm of Glacier Bay, and continuously collected data at intervals of 30 seconds for a period of about 7 days. Subsequent reoccupations of the base stations and landslide monuments in August of 2003 and 2004 were intended to measure landslide movement rates.

A slide-impact source model, consistent with the findings of Fritz and others (2001) and Mader and Gittings (2002) for waves generated by the 1958 Lituya Bay slide, was used to specify the initial conditions for wave propagation in Glacier Bay. A number of empirical methods were used to calculate wave height runup and velocity. Wave trains of long duration are caused by oscillations at the source that are characteristic of impact-type generating mechanisms. Also contributing to the long duration is cross channel-resonance and the site-specific response at locations outside Tidal Inlet.

Results

The crown of the main scarp is arcuate, but irregular along its length, with the highest part of the crown at an elevation of about 700 m. The estimated distance from the base of the main scarp downslope to the center of the toe of the landslide block is about 500 m and the maximum slide width is about 1,230 m. With an estimated maximum depth of 30 m of the surface rupture, the estimated volume of the Tidal Inlet landslide ranges from 5 to 10 million m³.

Annual GPS measurements of one marker indicated that horizontal movement of 7.9 cm (with assessed error of ± 1.5 cm) occurred in the downslope southerly direction between July 2002 and August 2004. There was no detectable vertical motion within the limits of uncertainty. Two other markers that were annually measured between 2003 and 2004 also showed movement of similar magnitude and direction providing strong evidence for consistent very slow movement of the landslide body. The continuing movement of the landslide suggests potential destabilization and triggering of more rapid landslide movement by earthquakes or climatic triggers, such as intense rain storm or rapid snowmelt. Numerical simulations of waves generated by a major subaerial slide into Tidal Inlet indicate that significant wave activity would occur in the western arm of Glacier Bay for more than several hours (Geist and others, 2003). Assuming the maximum landslide volume impacting Tidal Inlet, a maximum of 76 m wave height and wave runups on the opposite shore up to 200 m were calculated using empirical equations. Estimates of wave speed range from 45-50 m/s. It is likely that very high amplitude waves would persist throughout Tidal Inlet. Outside the Inlet, waves of significant amplitude (>10 m) may occur in shallow water regions, especially near the mouth of Tidal Inlet. In the deep waterways of the western arm of Glacier Bay, estimates suggest the wave amplitude

would decrease. In contrast, a lower volume landslide would generate waves with shorter periods throughout the first arrivals and coda of the wave train. Overall, these estimates suggested that differences in wave characteristics among locations in Glacier Bay would primarily depend on the local bathymetry, while changes in slide parameters would primarily influence the overall amplitude of waves.

Near the mouth of Tidal Inlet, the amplitude of waves is greatest within approximately 40 minutes after the slide enters the water. Moreover, the first arrivals there and elsewhere in the vicinity of Tidal Inlet are likely to be long period waves (periods of up to 1 minute) and approximately unidirectional: i.e., can be characterized as cylindrical waves emanating from the mouth of Tidal Inlet. In contrast, the coda of the wave train is caused by multiple reflected, scattered, and trapped waves that are broadband and have a wide range of incidence angles.

Discussion and Conclusions

Although the wave heights and runup modeled in Tidal Inlet and Glacier Bay are considerably less than those experienced during the 1958 landslide in Lituya Bay, the risk associated with a catastrophic landslide may be very high due to the frequency of large cruise ships that pass Tidal Inlet for several months every day during the summer. More detailed three-dimensional wave modeling is needed to assess the potential wave height and velocity that would travel beyond Tidal Inlet into the western arm of Glacier Bay, taking into account refraction and reflection of waves. The response of cruise ships in the region to these waves likely depends on the size and speed of the slide and on which part of the wave train the ships encounter.

Management Implications

Further monitoring of landslide movement by GPS or satellite imagery is necessary to periodically evaluate the stability of the Tidal Inlet landslide. Real-time monitoring of the landslides could be achieved by telemetered movement data. A threshold in movement rate could be defined at which alarms are issued to vessels in the area. A complimentary remote observation system would detect landslide-induced waves, which could be used to warn ships approaching the area. The input of nautical engineers is required to determine the magnitude of impact suffered by a variety of ships to these impulse waves.

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Cravasses break the surface of this glacier. (Photograph by Bill Eichenlaub, NPS.)