CHAPTER 101

The Generation of Waves by a Landslide: Skagway, Alaska—A Case Study

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1. Introduction

On November 3, 1994, at about 7:10 p.m. Alaska time, a combined aerial and sub-aerial landslide, which was not seismically induced, occurred at a railway dock on the eastern side of the harbor at Skagway, Alaska. A small portion of the landslide, consisting in part of rip-rap, was initially above water. The submerged landslide material was composed of loose alluvium accumulated along the eastern side of the harbor on an underwater slope with an average angle between 0 deg. and 30 deg. Witnesses reported waves 30 ft to 36 ft high at the eastern side of the harbor. The slide and the generated water waves claimed the life of one construction worker and caused an estimated $21 million damage. A map of the Skagway Harbor is presented in Fig. 1 showing the location of the landslide and the surrounding area including the Taiya Inlet which is an arm of the much longer Lynn Canal.

A floating dock used as an Alaska state ferry terminal is located in the middle of the harbor at the end of a 660 ft long jetty, and a small boat harbor is located near the east side of the harbor. The chains which moored the floating dock were broken during the event.

At the time of the landslide the tide elevation was at about –4 ft MLLW; the tide range at Skagway varies from about 9.8 ft to about 24.6 ft over a month. The record from a tide gage located at a dock on the west side of the harbor is presented in Fig. 2 showing the waves generated by the landslide. The tide gage trace is truncated for extremely low water surface elevations because, for those readings, the travel of the gage recording pen was stopped by the chart paper guide.

The purpose of the study reported in this paper was to more fully understand the wave events which could have taken place in Skagway Harbor after the landslide. The interest is not in precisely modeling the landslide, but in defining the response of the harbor and of the moored floating ferry dock to waves generated by a moving boundary which is used as an analogy to the landslide for purposes of wave generation.

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Three aspects of the problem will be investigated and will be discussed in subsequent sections. The first deals with the dynamics of a gas-purged nitrogen bubbler tide gage which was of the same type as used in Skagway. The dynamics of the tide gage were determined experimentally in the laboratory, and the response is presented in this discussion. The second aspect is the response of Skagway Harbor to the waves generated by the transient motion of a section of the harbor boundary. This was investigated primarily to simplify the problem of the generation mechanism for landslide induced waves. The transient waves generated by the moving boundary have a similar ability to induce oscillations in the harbor as waves generated by an aerial and a sub-aerial landslide. With the harbor connected to a large open region, i.e., the Taiya Inlet, the questions are how energy generated by a moving boundary (representing the landslide) propagates across the harbor and into the inlet and what is the frequency content of this energy at various locations within Skagway Harbor. The third portion of the overall problem deals with the failure of the floating ferry dock mooring chains. An analytical model was developed for the response of the moored-floating dock to incident waves, and combined with wave spectra determined from the harbor response model, the parting of the mooring chains which was observed at Skagway was investigated qualitatively.

2.   The Landslide Event

In this section the characteristics of the landslide and the generated waves will be discussed along with some observations made by witnesses of the event (see Watts and Petroff (1995)). There were four major docks in Skagway Harbor prior to the landslide: an Ore Loading Dock situated adjacent to a jetty that forms the west side of the harbor and is the site of the tide gage location; the Ferry Terminal Floating Dock located in the middle of the harbor at the end of a 660 ft long landfill jetty; the Broadway Dock immediately west of the Ferry Terminal Dock and jetty; and the White Pass Company Railway Dock located along 1312 ft of the eastern shore of the harbor and immediately south of the small boat harbor. (These can be seen in the map presented as Fig. 1.)

The underwater landslide on November 3, 1994 destroyed the southern 984 ft of the White Pass Company Railway Dock. Construction work was underway at the White Pass Company Railway Dock, and the northern quarter (328 ft) of the dock had been cut away from the southern three quarters (984 ft) to replace wooden piles with steel sheet pile cells. Several construction workers standing on the northern quarter of the dock watched the landslide and the southern part of the dock disappear into the water. The job superintendent estimated the total time from the beginning of the slide to the total loss of ground at between 15 to 20 seconds. The wave generated by the landslide was described as a "wall of water" by the survivor who escaped from one of the sheet pile cells that disappeared in the landslide. At about the same time it was observed by two of the three witnesses that a barge alongside the White Pass Company Railway Dock appeared to be level with the remaining northern portion of the dock, providing evidence of a positive wave generated by the landslide and/or a wave reflecting off the shoreline.

The Ferry Terminal Dock located at the center of the Skagway Harbor was moored with thirteen chains each with a scope such that it would allow for the relatively large vertical movement of the dock caused by the tide range. The chains consisted of both 1.5 in. diameter and 2.5 in. diameter chain links (a submerged unit weight of about 48 lbs/ft), and links were broken on all thirteen chains as a result of the dock movement. Observers reported that the dock was not overtopped

by waves. However, tall lamp posts located on the dock were all buckled at the base with the poles bent westward indicating that there must have been either a significant eastward acceleration of the dock or large westward deceleration.

3. The Tide Gage Response

The tide record shown in Fig. 2 was measured using a gas-purged nitrogen bubbler gage (see Young, 1977). The gage records the change in water level by sensing the change in hydrostatic pressure at the open end of a gas filled tube, termed the orifice chamber, which is secured beneath the still water level. For the case of a steady water surface the pressure of the gas throughout the tube is approximately equal to the pressure of the water at the gas-water interface at the end of the tube. For example, as the pressure increases with the rising tide, the gas in the tube compresses to reach equilibrium and shifts the gas-water interface. By supplying a regulated flow of gas the interface is kept at the end of the tube throughout the tidal range. The other end of the tube is connected to a bellows and through a mechanical linkage to a pen recorder. A needle valve located between the end of the tube and the bellows can be adjusted to damp out pressure fluctuations due to normal short period wave activity. The adjustment is subjective and is determined on-site by the gage operator depending on the ambient wave conditions. Thus, as the pressure at the open end of the tube changes the bellows expands or contracts thereby providing a tide record or marigram. The tube length for the Skagway bubbler tide gage was about 150 ft. Due to effects of compressibility, the bellows arrangement, the linkages, and especially the setting of the damping valve this type of transducer has a dynamic response which varies as a function of the frequency of the pressure fluctuation at the open end. To correctly interpret the tide gage record presented in Fig. 2 for waves with periods much shorter than the tide, it was necessary to independently calibrate the bubbler tide gage.

A calibration system was designed to determine the dynamic response of the nitrogen bubbler tide gage to an imposed sinusoidal pressure. The orifice chamber was immersed in a partially water-filled pressure chamber which could have a time-varying air pressure impressed above the water surface. The air pressure was varied sinusoidally with an adjustable period from 10 sec to about 1200 sec. The dynamic response of the gage obtained with this calibration system is presented in Fig. 3. The ratio of the maximum wave amplitude indicated on the chart to the imposed wave is the ordinate and the period of the oscillation is the abscissa. Based on information that the ambient wave condition on the day of the landslide was 3 to 4 foot waves of 10 sec, the gage was adjusted so that the response from this wave condition was barely observable. This corresponded to a needle valve opening of 3/4 turns. Additionally, the responses at other valve positions were tested including 1/2 and 3/8 turns as suggested by NOAA field personnel. For excitation periods greater than about 1,000 sec (16 min) the response is nearly unity, but as the excitation frequency increases, i.e. the wave period decreases, the signal is damped dramatically. For example, at a period of about 3 min, the response, a/a_0, varies from 40 % to 75 % depending on the needle valve setting. At a wave period of approximately 20 to 30 sec the response is between 5 % and 25 %.

4. A Numerical Model for Harbor Response

A finite element model based on the depth averaged equations of motion was developed to determine the wave response of Skagway Harbor to a moving a section of the boundary corresponding to the region of the observed landslide. This

somewhat simplified numerical model was chosen, since it was believed that the important elements of the landslide-induced waves could be generated in this manner. Indeed the object of this study was to investigate the wave motions induced by a transient disturbance in this harbor and to develop wave spectra at various locations. These results will help to explain how the floating ferry dock mooring system was damaged.

As a guide to the concept of using a boundary motion to represent a material landslide, simple experiments were conducted in a laboratory channel (with depth h = 28.2 cm) by a two-dimensional triangular solid block (with horizontal and vertical edges 12.4 cm long) moving on a 45° slope. The horizontal face was initially 3 cm above and submerged 3 cm below the still water surface. The water-surface time histories recorded at the toe of the slope are presented in Fig. 4 with the nondimensional wave amplitude plotted as a function of nondimensional time. Offshore of the generation region, a lead positive wave is followed by a negative wave with the part-aerial landslide producing a larger positive wave than the sub-aerial one. The positive wave is generated by the forward advancing vertical front face of the block while the negative wave is generated by the downward moving horizontal face. For both model landslides the wave has some similarity to one cycle of a sinusoid. Therefore, in the numerical model, a boundary motion was chosen that would generate a similar wave near the source.

Three motions were considered for a 984 ft section of the east boundary of Skagway Harbor corresponding in length to the section of the White Pass railway dock's foundation which failed. The motions were: a combined positive and negative motion with a period of 20 sec and an amplitude of 20 ft/sec, and separately, a positive motion and a negative motion alone each with a maximum amplitude of 20 ft/sec and a duration of 10 sec. The maximum velocity was based on the both the estimated time of the landslide event and the thickness of the slide. Since the equation of motion was depth averaged, the boundary generator moved as a piston.

The governing equations used for the present finite element model are similar to those used by Leendertse (1967). (Leendertse (1967) used a finite difference method for his solution.) The equations of motion used in the two propagation directions are as follow:

for the x-direction:
$$\frac{Du}{Dt} = -g\frac{\partial\eta}{\partial x} + 2\Omega(\sin\Phi)v - \frac{\tau_{bx}}{\rho(h+\eta)} \qquad (1)$$

and for the y-direction:
$$\frac{Dv}{Dt} = -g\frac{\partial\eta}{\partial y} + 2\Omega(\sin\Phi)u - \frac{\tau_{by}}{\rho(h+\eta)} \qquad (2)$$

where u and v are the velocity components in the x and y directions, g is the acceleration of gravity, η is the amplitude of the wave, Ω is the earth's rotational speed, Φ is the latitude, τ_b is the bottom shear stress with direction indicated by the subscript, and ρ is the fluid density. The second term on the right in Eqs. 1 and 2 is termed the Coriolis acceleration. The last term is the bottom friction expressed in terms of the shear stress along the bottom. The continuity equation for a long wave in the x and y directions is:

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\left[(h+\eta)u\right] + \frac{\partial}{\partial y}\left[(h+\eta)v\right] = 0 \qquad (3)$$

These equations have been solved using a finite element technique with finite difference in time. The grid used is shown in Fig. 5. For this model, the shoreline is considered perfectly reflecting. The portion of the shoreline which was impulsively moved to represent the landslide is shown. Along the region of the model denoted as ABCDE the boundary of the numerical model is non-reflecting and represents the so-called "open sea". Wave energy can pass through this boundary but will not be reflected back to the harbor. However, at the limit of the modeled Skagway Harbor, due to the change in width of the harbor entrance compared to the width of the outer region, reflection occurs. This "mis-matching" at the entrance is one reason for the "ringing" which was seen in the tidal record presented in Fig. 2. An open harbor entrance acts to some extent like a leaky closed boundary allowing energy to escape and some to be reflected back into the harbor; this is the basis for resonance. Although the model is three-dimensional the velocities are depth-averaged. Thus, it is expected that the information obtained from the model may be more qualitative than would be obtained from a more general set of equations developed from the equations of motion incorporating a moving sediment mass. A velocity time history imposed along a section of the grid which corresponds to the location of the moving boundary was used as the forcing function for the model.

In Fig. 6 water surface contours corresponding to the ratio of the wave amplitude to the boundary motion are shown in the harbor at two different times after generation by the combined positive and negative boundary motion. An outline of the planform of Skagway Harbor is incorporated so that one can better appreciate the general outward spreading of the wave from the generation source; the ordinate is oriented north-south and the abscissa east-west. The upper plot corresponds to the time of the completion of the boundary motion. It is seen that the waves generally propagate toward the north–northwest as a spreading cylindrical wave. The positive maximum wave can be seen propagating toward the site of the Floating Ferry Dock while the negative wave is still relatively close to the generation boundary. As the wave spreads the wave amplitude decreases. The lower portion of the Fig. 6 corresponds to 40 seconds after motion begins. Toward the western side of the harbor, near the site of the tide gage, the waves propagate into the Ore Dock slip moving generally northward. Near the entrance to Skagway Harbor the wave amplitudes become very small; wave energy will propagate north and south in the inlet reducing further the wave energy which may reach the far shore of Taiya Inlet.

Three water surface time histories corresponding to three locations are presented in Fig. 7: at the Tide Gage (Location 8), at the Floating Ferry Dock (Location 6), and at the head (landward end) of the Ore Dock slip (Location 2). At Location 6, both the wave amplitude and the wave frequency are larger than at either Locations 2 or 8. Apparently at the head of the Ore Dock slip the impulsive wave generated excites a mode of oscillation with a frequency much smaller than at Location 6. This also appears near the site of the Tide Gage (Location 8). The proximity of Location 6 to the boundaries must influence the frequency of the waves. Skagway Harbor does not reach steady state due to the leakage of energy past the entrance. The difference between the tide gage record presented in Figs. 2 and 7 is probably due to several factors. First, the boundary motion used in this model is a highly simplified; some features are reasonably represented while others are not. In addition, during the movement of the slide, the bathymetry within the

harbor changes and the numerical model does not incorporate these time-varying changes. Finally, and perhaps most important, the numerical model is depth averaged, and although some aspects of the waves are well represented by shallow water wave theory others are not. Therefore, the results from this model can only be considered an approximate representation of the events observed on November 3, 1994. It is believed that they do show the frequency characteristics of the waves in the harbor.

The energy spectra obtained at Locations 2, 6, and 8 are presented in Fig. 8 with frequency as the abscissa, and the energy normalized by the area under the spectrum is the ordinate. At each location, spectra corresponding to each of the three different boundary motions are presented. At the head of the Ore Dock slip and at the location of the Tide Gage, Locations 2 and 8, respectively, the major component is at about 0.007 Hz (wave period of 143 sec). It is recalled from Fig. 3 that the dynamics of the nitrogen bubbler tide gage will attenuate most high frequency energy so that only low frequencies will be present in the tide gage record. The most important feature of Fig. 8 is that in the vicinity of the floating ferry dock the predominant frequency is much larger than that observed at either Location 2 or 8. The frequency of the peak energy is about 0.045 Hz (a period of 22 sec). This change in frequency as a function of location will be shown to be important with regard to the excitation of the floating dock.

5. The Response Of The Floating Ferry Dock

A schematic is presented in Fig. 9 showing the Floating Ferry Dock moored by chains, each with a submerged weight of approximately 48 lbs/ft. As shown in the lower portion of Fig. 9 these chains are arranged so the dock can rise and fall with the tide. The dock and the chains form a dynamic system with the chains and their catenary shape defining the restraining and restoring force associated with dock motion. As the chain lifts up from the seabed or is laid down the changing weight and resultant tension in the suspended portion of the chain provide a non-linear restoring force. This is shown in Fig. 10 for one typical chain. The abscissa is the horizontal displacement of the mooring point on the barge, and the ordinate is the restraining force associated with this displacement.

A simplified analytical model of the moored Floating Ferry Dock was developed primarily to determine the important range of frequencies for the excitation of the dock. These could then be compared to the spectrum corresponding to Location 6 in Fig. 8 to assist in inferring the cause of the observed chain failure. The method used to develop the equation of motion of the dock was presented by Raichlen (1965). The floating body was excited by a volume averaged acceleration and velocity, i.e. the average over the displaced volume of the dock of the acceleration and velocity in a small amplitude long wave. It was assumed that viscous damping and wave damping were small and could be neglected, and that dock motion was controlled primarily by inertial forces. Resistance to motion was due to the varying weight of the mooring chains. Although waves approach the barge obliquely in the harbor model, for the motion analysis, it was assumed that waves approach from an easterly direction and that the barge's motion would then be east-west and defined as the x-direction. Considering the shape of the curve of restoring force vs. displacement, the simplified equation of motion in the absence of damping is as follows:

$$\frac{d^2x}{dt^2} + \alpha x + \beta x^3 = \frac{dU}{dt} \qquad (4)$$

The constants α and β in Eq. 4 which define the restoring force are based on a total of five chains acting simultaneously. The volume averaged acceleration dU/dt is determined from small amplitude wave theory as:

$$\frac{dU}{dt} = \frac{ag}{kLD}\left[\frac{\sinh kh - \sinh ks}{\cosh kh}\right] \sin kL \cos\sigma t \qquad (5)$$

where a is the amplitude of the wave, k is the wave number, L is the length of the barge in the direction of wave propagation, i.e. 120 feet, D is the draft, h is the depth, s is the distance from the bottom to the keel of the barge, and σ is a circular wave frequency. For long waves Eqs. 4 and 5 become:

$$\frac{d^2x}{dt^2} + \alpha x + \beta x^3 \approx a\sqrt{\frac{g}{h}}\ \sigma \cos\sigma t \qquad (6)$$

This equation has the form of the Duffings equation with the exception that the forcing function is linearly proportional to the circular frequency, σ. This equation is evaluated by assuming a motion for the horizontal displacement of the vessel from the at-rest-position of:

$$x = X \cos\sigma t \qquad (7)$$

as discussed by Stoker (1963). Although this may be a significant simplification, the assumption of Eq. 7 leads to the development of the response curves to show the important forcing frequencies for this problem.

The response curves for this non-linearly moored body obtained in this manner are presented in Fig. 11 where the amplitude of motion of the dock is plotted as a function of excitation frequency for given wave amplitudes. A so called "backbone" curve represents a zero wave amplitude. The response to the right of this curve is out-of-phase with the excitation and to the left it is in-phase. Referring to Fig. 8, the important wave frequency present at Location 6 (the location of the floating ferry dock) is approximately 0.045 Hz ($\sigma = 0.283$ rad/sec), i.e., a wave period of 22.2 sec. The response curve in Fig. 11 shows that this excitation frequency is near the resonant frequency of the moored dock. For a wave amplitude of one foot and a circular frequency of 0.283 rad/sec, the response of the barge is approximately four times the forcing function. Perhaps more important, as the wave height increases from zero at this frequency the motion increases until a minimum of the response curve is reached for the given excitation amplitude. The motion will jump to the higher branch of the curve changing suddenly from out-of-phase to in-phase. This can create significant dynamic chain stresses. Thus, it is believed that although the observed wave periods at the tide gage were relatively large, because of the influence of the geometry and the proximity of the dock to the harbor boundaries, the higher frequency which is observed at the site of the floating ferry dock might have led to the mooring line and lamppost failures.

An example of the motion time history of the dock is shown in Fig. 12 for an excitation based on the spectrum presented in Fig. 8 using Eq. 6 to represent the excitation spectrum by the superposition of forcing functions :

$$\frac{d^2x}{dt^2} + \alpha x + \beta x^3 \approx \sum_{i=1}^{N} \left[a_i \sqrt{\frac{g}{h}} \, \sigma_i \cos \sigma_i t \right] \qquad (8)$$

where i is the frequency component of the forcing function varying from i = 1 to N, and the phase angles have been arbitrarily set equal to zero. The frequencies and the amplitudes of the components are shown in the table accompanying the figure. Significant motions approaching amplitudes of ± 10 ft can be seen for the assumed waves. This corresponds to an amplification factor, i.e., the ratio of the amplitude of the horizontal dock motion to the average of the amplitudes of the wave components, of approximately fifteen. Thus, the dynamics of the mooring system could have been a major contributor to the failure of the mooring chains at Skagway.

5.   Conclusions

The following major conclusions can be drawn from this study:

1. The gas-purged pressure recording (bubbler) tide gage with normal operating settings has a response (measured amplitude/actual amplitude) of 40 % to 75 % for waves with periods of 3 min and 5 % to 25 % for waves with periods of 20 sec.
2. An impulsive wave generated in Skagway Harbor by the simple motion of a section of the coast can induce groups of complex waves composed of a wide range of frequencies.
3. The frequency content of the transient waves generated by the boundary motion is strongly dependent on location.
4. Different forms of the boundary motion tend to generate similar spectral energy distributions at the same location in the harbor.
5. The damage to the floating ferry dock observed at Skagway may have occurred due to the combined effect of the mooring dynamics of the dock and the frequency content of the waves at that location.

6.   Acknowledgments

7.   References

Leedertsee, J.J., "Aspects of a Computational Model for Long-Period Water Wave Propagation", Memo KM-5294-PR RAND Corp., Santa Monica, CA, 1967.
Raichlen, F., "Wave-Induced Oscillations of Small Moored Vessels", W.M.Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Report No. KH-R-10, 1965.
Stoker , J.J., "Nonlinear Vibrations", Interscience Publishers, Inc., 1963.
Watts, P. and Petroff, C.M., Report of Visit to Skagway, Alaska, December 1994", Tsunami Bulletin Board, January 1995.
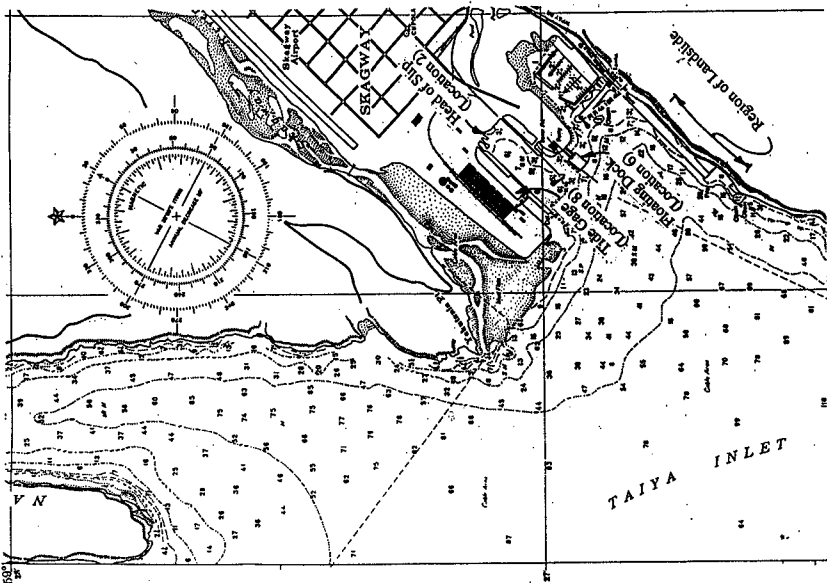Young, S.A., "User's Guide for the Gas-Purged Pressure Recording (Bubbler) Tide Gage", NOS, NOAA, 1977.
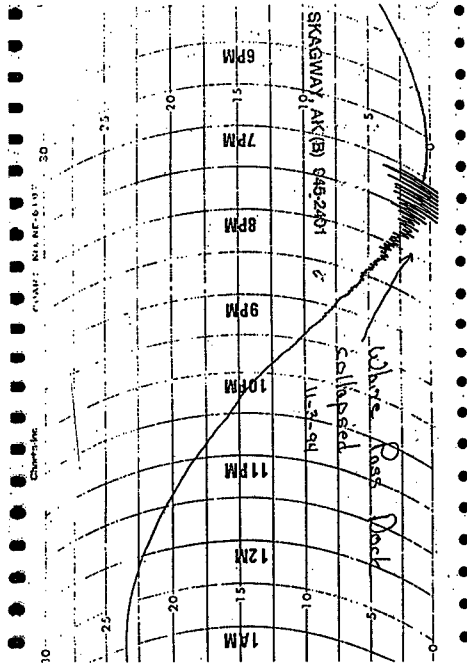
Figure 2 Tide gage record for November 3, 1994
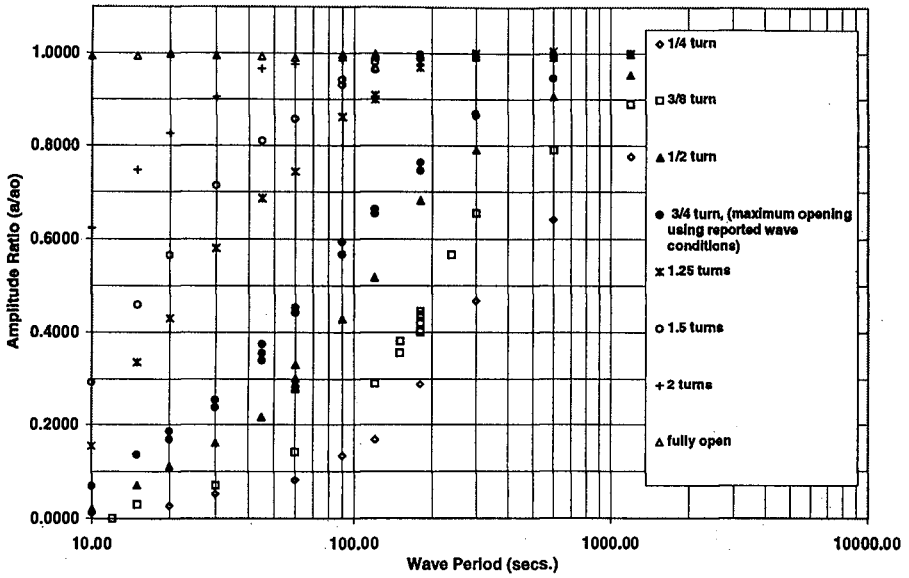
Figure 1 Map of Skagway Harbor
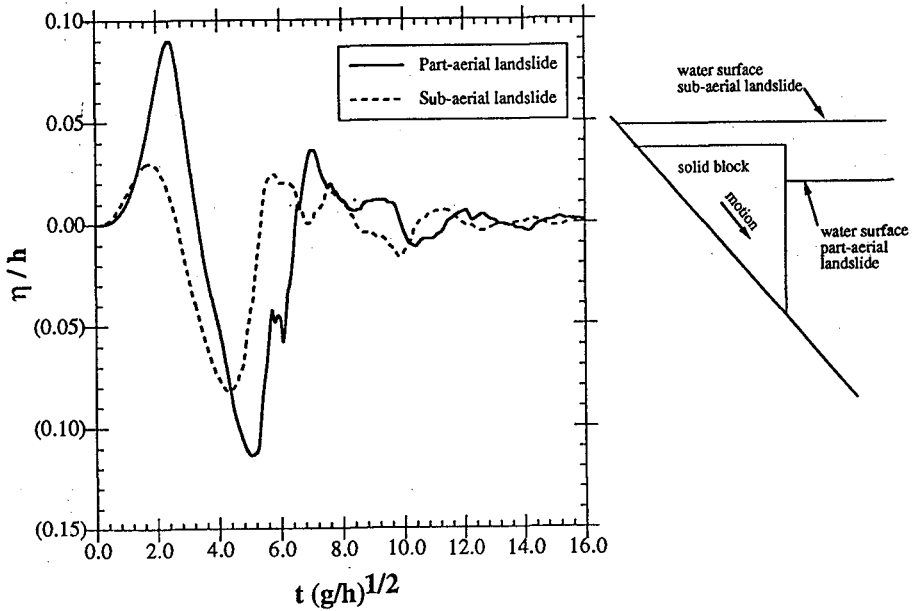
Figure 3 Measured tide gage response

Figure 4 Water waves generated by a simple laboratory model of a part-
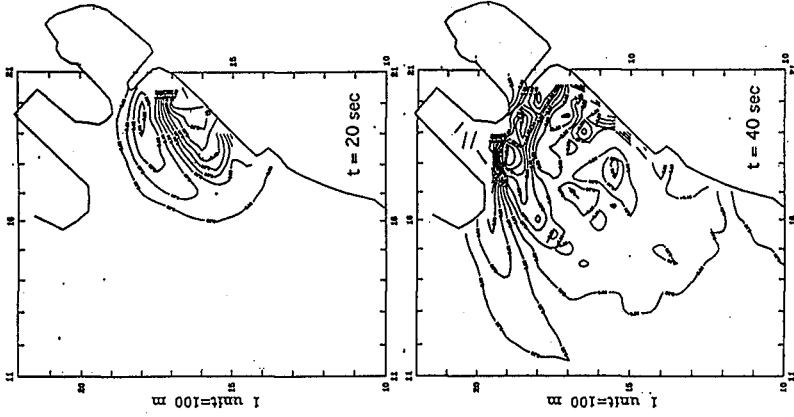aerial and sub-aerial landslide

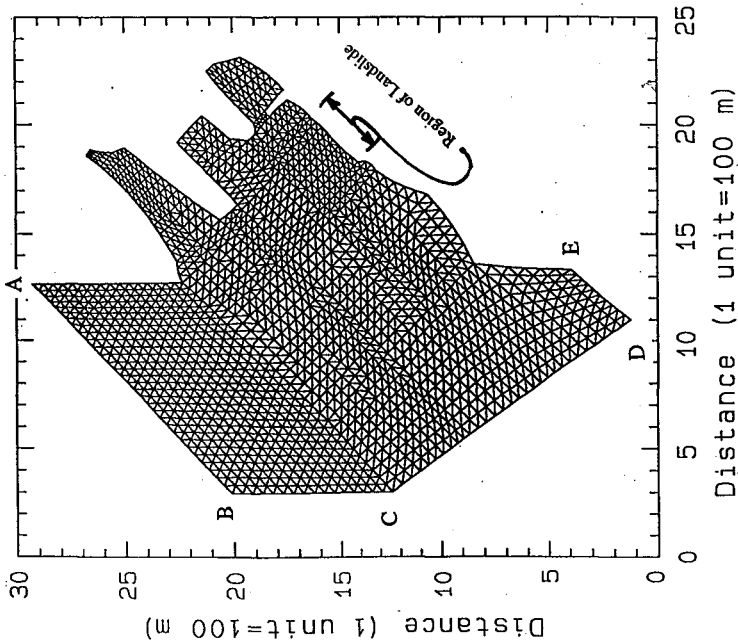Figure 6 Normalized water surface contours at the end of wave generation (t = 20 sec) and at t = 40 sec.

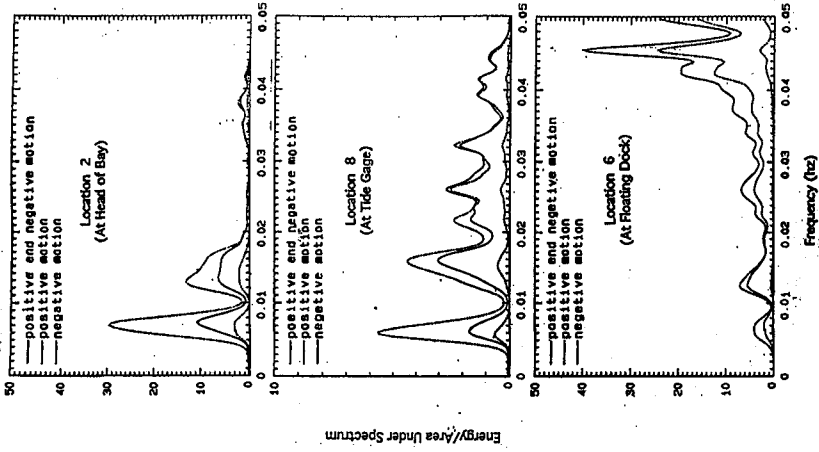Figure 5 Grid for a finite element model of wave propagation in Skagway Harbor
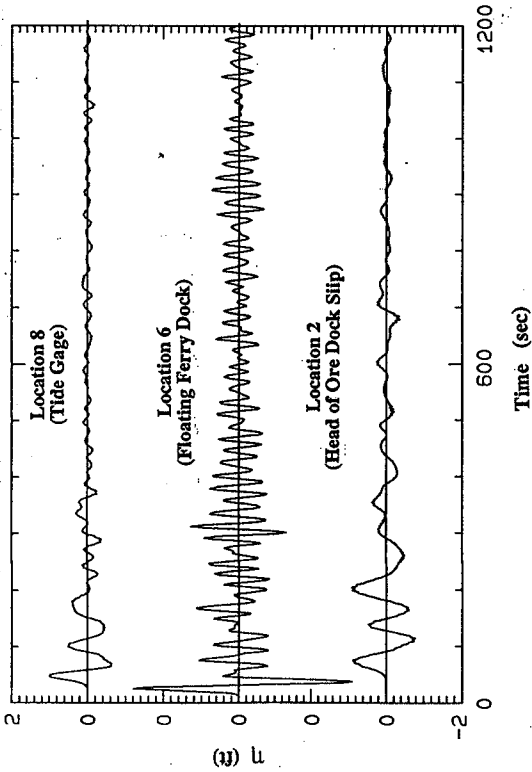
Figure 8 Wave spectra at three locations in Skagway Harbor for three boundary motions

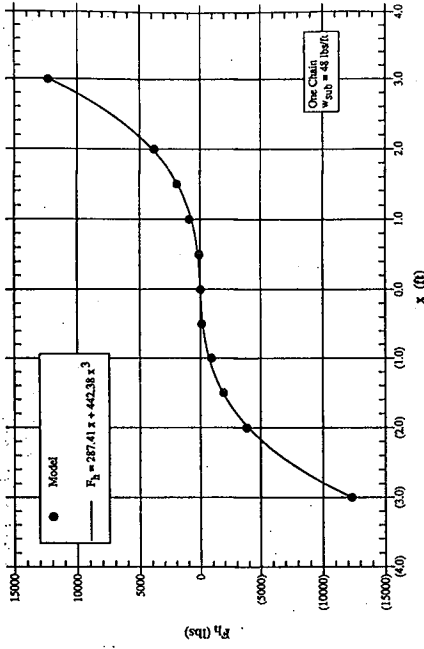Figure 7 Water surface-time histories at three locations in Skagway Harbor
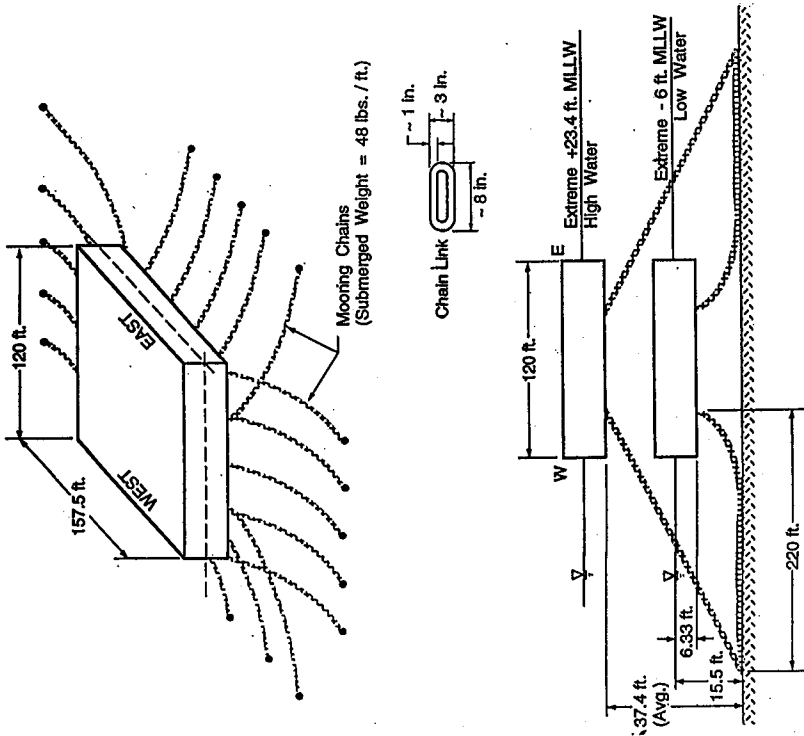
Figure 10 The variation of the restoring force as a function of horizontal displacement for one chain

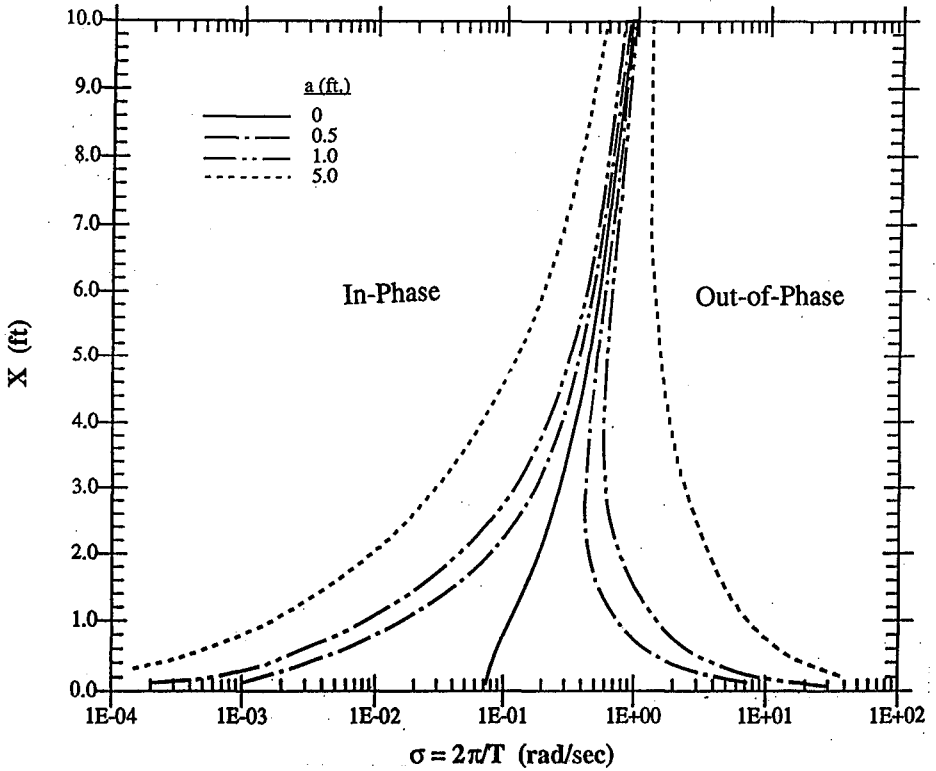Figure 9 Sketch of mooring configuration for Floating Ferry Dock

Figure 11   Response of moored Floating Ferry Dock as a function of wave
              amplitude and circular frequency

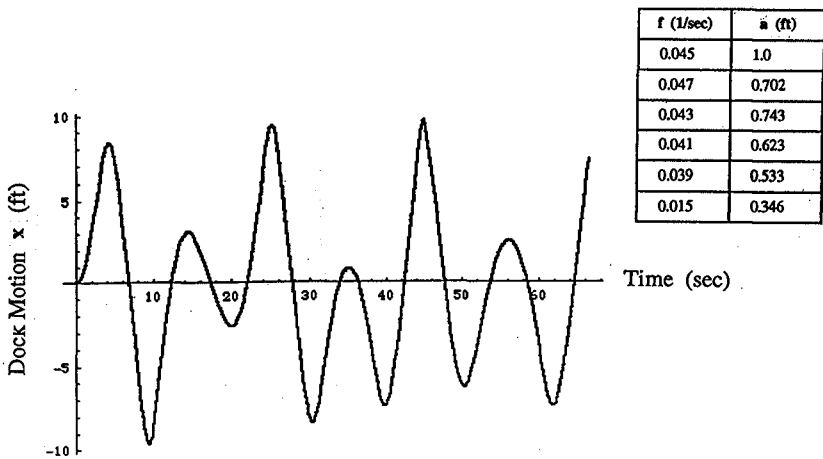| f (1/sec)	a (ft)
0.045	1.0
0.047	0.702
0.043	0.743
0.041	0.623
0.039	0.533
0.015	0.346

Figure 12   Horizontal motion time history for moored Floating Ferry Dock for
              a given wave input