Suboceanic Landslides

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Although normally thought of as being a feature of mountainous regions, landslides can happen almost any place where the ground surface slopes. In fact, some of the largest landslides on Earth occur underwater. Suboceanic, or submarine landslides can involve the movement of rocks and sediments entirely beneath the sea, or they can begin as partly above-water landslides that later enter the ocean. Like open-air landslides, submarine landslides often strike steep inclines ($\sim 10^0$). Unlike open air slides, submarine landslides hit very slightly dipping terrain ($<1^0$) too. Many historical and prehistorical landslides have raked the slopes of deep ocean trenches and continental margins where strong earthquakes recur periodically. Seismic shaking probably triggered these slides. Other landslides however, locate on seismically quiet continental passive margins, such as the east and west edges of the Atlantic Ocean, and on the flanks of oceanic island volcanoes such as Hawaii and the Canaries. Best evidence suggests that the potential for suboceanic landslides exists pretty much globally, whether in tectonically active or tectonically inactive regions. A primary hazard of submarine landslides, like their land bound relatives, is the wasting of man-made structures along their path. The newest research however, perceives that undersea slope failures present an additional threat -- landslide-generated tsunami waves.

The first fully submarine landslide to be recognized dates to 1929 when between 300 and 700 km^3 of sediment slid off the top of the continental slope south of Newfoundland in a thin but broad flow that passed just west of the wreck of the *Titanic.* The mass of fluidized sediment plunged into the depths of the Atlantic at speeds near 80 km/h. During its course, the landslide mass turned into a giant flow of turbulent, sediment-laden water that successively broke several transatlantic telegraph cables connecting America and Europe. Interestingly, the timing of the cable breaks established the speed of the landslide. Little recognized for many years after the event was the landslide-generated tsunami that struck sparsely populated coasts of Newfoundland and Nova Scotia. Waves 10 m and more high killed nearly 30 people. Some seventy years later in 1998, another landslide (this one definitely initiated by an earthquake) swept the submarine slopes north of Papua New Guinea. In contrast to the 1929 event, the landslide mass held together as a thick slab that was later found at the bottom of the slope. The New Guinea slide too raised a tsunami. On this occasion, large villages on the adjacent coastline stood in harm's way and more than 2000 people died in the wave. Because the 1998 wave seemed to be too big to have been generated by the earthquake, researchers suspected and later verified, that the tsunami had a "landslide assist". Subsequently, scientists implicated submarine landslides in other historical tsunamis that looked too large for the earthquakes originally blamed for them. Most notably, studies revealed that the source region of the 1^{st} April 1946 Unamak Island (Aleutian Islands) tsunami contained a prominent, fresh landslide similar to that discovered off Papua New Guinea.

That 1946 tsunami, one of the biggest in historical time, caused major damage and death as far away as Hawaii and the Marquesas. Even this event however, is likely to have been dwarfed by tsunamis produced by submarine landslides of pre-history. The Storegga landslides, the largest continental slope failures well-documented by geological observation, struck off the coast of central Norway between 5000 and 50,000 years ago. The largest of these had a volume ten times greater than the 1929 Newfoundland landslide and transported material 500 km, halfway to Greenland. Curiously, the existence of the Storegga landslide came to light partly because of the identification of layers of tsunami-deposited sediment in far-away Scotland and Holland. Submarine landslide potential near

Storegga continues to receive a great deal of scientific study due to the presence there of Norway's richest reserves of petroleum and the country's huge offshore infrastructure in drilling platforms and sea bed pipelines. A Storegga slide today would wipe away many millions of dollars of investment.

Computer experiments show that the efficiency of tsunami generation increases with the speed and volume of the landslide. Odds are, landslides even bigger and faster than Storegga have produced larger tsunami. The "kings" of suboceanic landslides are giant slope failures on oceanic islands. (We know that these landslides exist from their residual debris.) Starting far above sea level, "flank collapse landslides" as much as 3 km thick, sliding down into the water at speeds nearing 360 km/h could induce waves with initial heights of several hundred meters. Some scientists believe that coral rubble beds discovered 100-200 m up the side of the Hawaiian Island of Lanai were actually laid down by one such tsunami. Ongoing and recent movements of the flanks of a number of oceanic island volcanoes including Kilauea in Hawaii and the Cumbre Vieja on La Palma in the Canary Islands hint that one of these may break down during an eruption in the not-too-distant future. Fortunately, giant flank collapses are rare, however volcanic landslides of a few cubic kilometers volume have punctuated the historical past. Those at Japan's Oshima-Oshima volcano in 1741, and Papua New Guinea's Ritter Island volcano in 1888, rolled 4 m tsunami onto coastlines 600 to 1000 km distant.

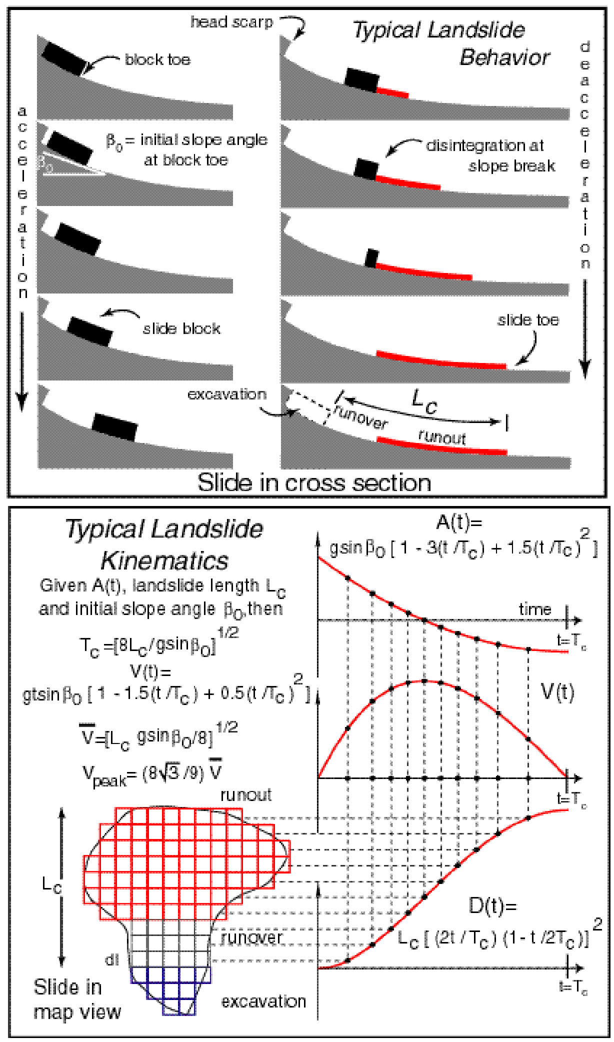

Figure 1. (*Top*) Behavior of a typical suboceanic landslide shown in cross section. (*Bottom*) Typical suboceanic landslide in map view. Curves to the right describe a mathematical model of the acceleration A(t), velocity V(t) and distance D(t) of the slide front versus time.

To move suboceanic landslides to a firm scientific foundation, we must quantify their kinematics in an elementary but realistic manner. Landslide kinematics specify the position, velocity and thickness of the material as it transits down-slope. Figure 1 (top) shows a typical suboceanic landslide in cross section. Usually, landslides begin when a *slide block* pulls away from a slope, leaving an *excavation* with its signature *head scarp*, a cliff 10's to 100's of meters high. The block accelerates downhill and crosses, more or less as a coherent mass, a region of the slide scar termed the *runover*. At the *slope break* where the incline begins to level out, the slide mass often disintegrates, if it hasn't already, into a *runout sheet.* The runout is much thinner than the block but it covers a much larger area. Material excavated at the head of the slide carries across the runover and deposits in the runout. The runout represents the deacceleration phase of the slide that terminates at the *slide toe*.

Figure 1 (bottom) sketches a typical suboceanic slide in map view. As pictured, submarine landslides often have an up-slope neck containing the excavation and the runover, and a broad down-slope fan containing the runout. The curves to the right of the slide map illustrate a mathematical model of the history of slide motion. In particular, the middle velocity curve V(t) shows the acceleration and de-acceleration phases mentioned above. These formulas for slide motion, together with the slide shape and thickness, comprise the kinematics needed to compute slide-generated tsunami waves. Note that in this description, landslide duration T_c and mean slide velocity $\bar{V}$ depend on the length L_c of the slide from the *block toe* to the slide toe and the *initial slope angle* β_0 just below the slide block, as

$$T_c = \sqrt{8L_c / g \sin\beta_0} \qquad (1)$$

and

$$\bar{V} = \sqrt{g L_c \sin\beta_0 / 8} \qquad (2)$$

The g here represents the acceleration of gravity, $g=9.8\ m/s^2$. Most submarine slides span dimensions of L_c=5 to 500 km on slopes β_0 of 1 to 10 degrees. Formula (1) predicts slide durations of a couple minutes to over an hour. Formula (2) predicts average slide velocities of 10 to 150 m/s (36 to 540 km/hr). While these velocities seem high, be aware that landslide speeds usually lag the $\sqrt{gh}$ speed of the tsunami in an overlying ocean of depth h.

Figures 2 and 3 picture tsunami generated from two submarine landslides -- one fairly small, and one quite huge. We imagine the small slide to occur on the continental slope just off San Pedro, the Port Facility for the City of Los Angeles, California. The slide has 1/2 km^3 volume, L_c=8 km, T_c=320 s, $\bar{V}$=25 m/s and a mean excavation thickness of 60 m. Although this slide is hypothetical, detailed sonar images of nearby sea floor reveal several landslide scars of similar scale -- a fact not overlooked by San Pedro Port directors! Above the slide, tsunami waves from this event reach 10-15 m height, but because the shoreline is so close (just 5-10 minutes travel time), the waves cannot spread out and disperse much before they beach. Worldwide, 1/2 km^3 landslides might befall some continental margin every

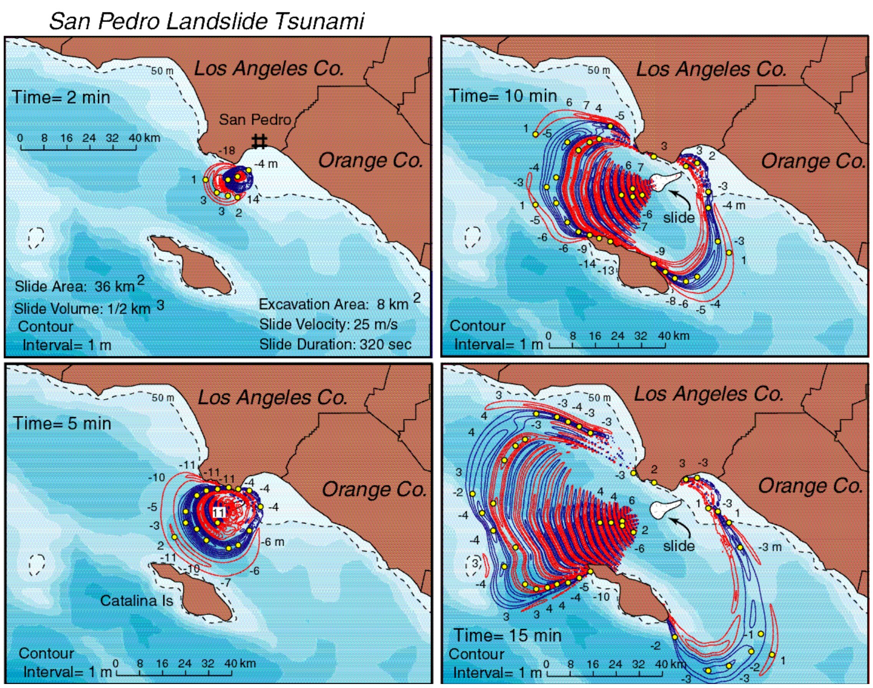

Figure 2. Computer simulations of tsunami produced by a hypothetical, but very plausible, suboceanic landslide off the United States west coast near Los Angeles. Panels show the waves at 2, 5, 10 and 15 minutes after the start of the event. Contour interval is 1 meter. During travel, tsunami form long trains of both upward and downward waves. Blue and red color elevated and depressed ocean surface respectively. The numbers sample wave height (positive above initial sea level; negative below initial sea level) in meters.

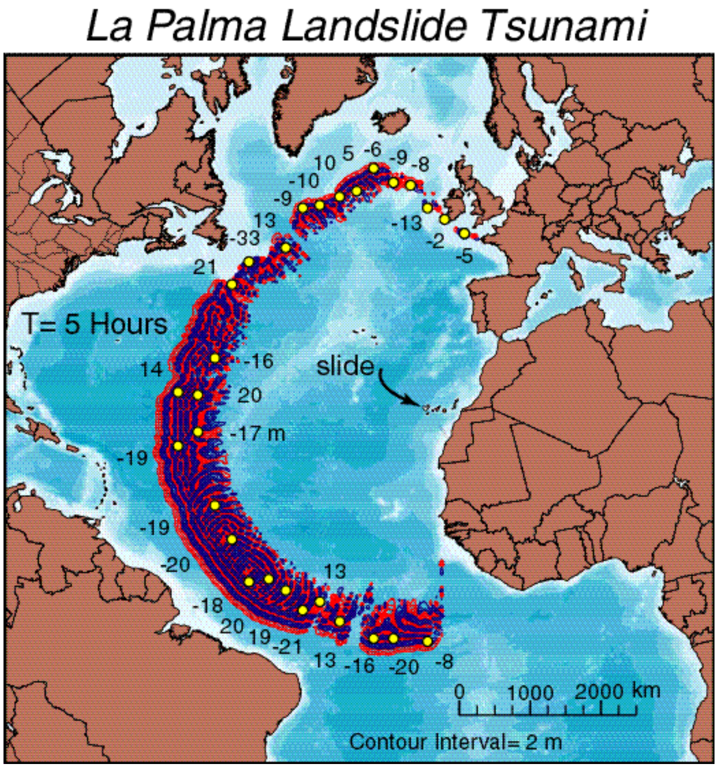

Figure 3. Computed tsunami 5 hours after a lateral collapse of Cumbre Vieja Volcano on the Island of La Palma, Canary Islands. Landslides of this volume (500 km^3) and velocity (100-150 m/s) can, and have, sent damaging waves across entire ocean basins. The numbers sample wave height (positive above initial sea level; negative below initial sea level) in meters.

few decades, so their hazard is palpable. Arguably, close-in suboceanic landslides could drop 3-4 m waves with little warning on just about any coast that has good exposure to the sea.

Figure 3 contours the tsunami expected from a lateral collapse of Cumbre Vieja Volcano in the Canary Islands. Recall that flank collapses represent the "worst case" submarine landslide. This La Palma slide involves 500 km^3 of material running out 60 km at a mean speed of 100 m/s. Although this incident is also hypothetical, the Canary Island chain has witnessed ten comparable landslides in the past million years. Considering all of the oceanic volcanoes in the world, a La Palma-scale collapse might knock somewhere once in 10,000 years or so. Our computer models predict that waves generated from collapse-scale submarine landslides could traverse entire ocean basins and retain 20 m height.

Evidence argues that suboceanic landslides are as common as landslides on land, and that the behaviors of the two groups share many elements. Like those on land, suboceanic landslides span several orders of magnitude in size and volume. Unlike landslides on land, submarine landslides lie hidden largely under the sea and so they wear a certain veil of mystery, not the least of which is a potential to parent tsunami. Vastly improved technologies in multi-beam sonar can now quickly map large swaths of sea floor to 1-meter resolution, easily spotting slumps and slope failures. With expanded use of these instruments, in a decade perhaps, scientists will have a much better census of submarine landslides and a clearer handle on their hazards.

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Related websites: (incomplete)

(PNG studies, Gerard Fryer's on the 1946 tsunami, NOAA on giant waves in the Atlantic)

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