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Tsunami Wave Height Dependence on Landslide Volume

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Abstract—Tsunami generation from submarine landslides depends mainly on the volume of the slide material and also on other factors which include: angle of the slide, water depth, density of the slide material, the speed with which the material moves, duration of the slide, etc. Based on an incomplete data set of volume *V* of slide versus maximum amplitude *H* of the resulting tsunami waves, gleaned through available literature, a simple linear regression relationship was developed. Another partial data set was developed also from published literature, on *V* versus *H* values, based on numerical models. It was found that the agreement between the results of the numerical simulations and the observations is rather poor. It is not clear why this is so, and which data set is of questionable relevance. This is not to cast doubt on numerical models that do not use volume of the slide in an explicit manner.

Key words: Landslide, volume, tsunami, amplitude.

1. Introduction

Intuitively one would expect the amplitude of a tsunami generated by a submarine landslide to be directly proportional to the total volume of the slide material (HARBITZ *et al.*, 1993) even though several other parameters also play important roles. These factors, in random order, are the following:

a) Depth at which the slide occurs, or rather, depth of water above slide.
b) Angle of the slide from the horizontal (or vertical) direction.
c) Total distance moved by the slide.
d) Duration of the slide.
e) Density of the slide material.
f) Coherent nature of the slide.
g) Grain size and spectrum.
h) Characteristic speed with which the slide moves.

It is quite possible that there are several other important factors not included in the above list. The aim of this study is modest and simple; to obtain a relationship between the volume *V* of the slide (expressed in millions of m^3) and the maximum amplitude *H* (in meters) of the resulting tsunami waves, based on observational data available in the published literature and to compare this relationship with the results

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of some numerical models. The observational data and numerical model results that are included in this study have been selected using only the following criterion, namely whether values for V and H are provided explicitly by the authors. If these are not provided, those events and models are not included here. Even though one can examine the accuracy of this data, it is beyond the scope of this short communication, and no attempt was made to verify the data.

If different numbers are provided by different authors for the same event, all the data have been used as separate entries, rather than using an average value. Even though, ideally a multivariate analysis could be performed using data on the parameters listed above, it is not attempted here and will form the basis for a future study.

The basic argument used here is that no matter how important all the other parameters may be, if there is no volume, there is no tsunami. It is that simple. Hence, the slide volume must remain the most important and basic parameter. The limited goal then is to obtain an order of magnitude relationship between V and H.

It should be noted that the relationship between the volume of the slide and the height of the resulting tsunami is phenomenological. Volume-based correlations are also a classical and reasonably successful approach in the field of geology, such as correlations for runout distances, etc. (BLYTH and FRETIAS, 1974; MCLEAN and GRIBBLE, 1979; and WHITTEN and BROOKS 1981).

2. State of the Art in the 1970s

Until the 1970s, there was no vast literature on numerical models for tsunamis from submarine landslides. However, there was considerable work on analytical models and laboratory studies. These approaches could not deal with realistic geometries and mostly dealt with very simplified situations.

MURTY and BROWN (1979) studied the tsunami of April 27th, 1975 from the submarine landslide in Kitimat Inlet on the coast of British Columbia, Canada, and MURTY (1979) simulated this tsunami using two different models. The results of an analytical theory and also an asymptotic theory agreed reasonably well with observations.

3. Observational Data

Table 1 lists the volume of the Slide V, the maximum height H of the tsunami wave, a brief description of the event, and the source of the data. Uncertainties in the data are clearly pointed out. At best, this table is only a partial list of landslides generated tsunami events worldwide and several important events are probably missing from the list.

Table 1

Observational data on landslide generated tsunamis worldwide

Event	V	H	Source
Vaiont Valley, Italy Oct. 1993	250	100	BOLT *et al.* (1975)
Kitimat, B.C., Canada April 27, 1975	55	7.6	BORNHOLD and HARPER (1998)
French Rivera near Nice Oct. 16, 1979	35 Average $V_{min} \approx 10$ (RZADKIWICZ *et al.*) $V_{max} \approx 65$ (George P.C.)	10 Anon, 1980	RZADKIWICZ *et al.* (1998) G. PARARAS-CARAYANNIS (1999) Personal Communication ANON (1980)
Lituya Bay, Alaska, U.S.A. July 9, 1958	31	30	HARBITZ *et al.* (1993). They refer to PUGH and HARRIS (1982)
Kitimat, B.C. Canada April 27, 1975	26	4.3	MURTY (1979)
Lomblen Island, Indonesia July 19, 1979	20 This is estimated based on discussions with colleagues, taking the following dimensions for the Slide Length = 2000 m. Width = 1000 m. Thickness = 10 m	11.1	TSUJI and HUSNI (1998)
Skagway, Alaska, U.S.A. Nov. 3, 1994	16.5	8.4	MADER (1997)
Skagway, Alaska, U.S.A. Nov. 3, 1994	15.3	10.7	CAMPBELL and NOTTINGHAM (1999)
Tafjord, Norway April 7, 1934	1.25	3 After the disturbance spread out	HARBITZ *et al.* (1993) Their Table 1 is confusing to me and hence the data of Table 1 is not used, Loen, 1905, $V = 5 \times 10^4$, $H = 40$ Tafjord, 1934, $V = 1$ to 1.5×10^6 LOEN, 1936, $V = 10^6$, $H = 74$
Skagway, Alaska Oct. 29, 1966	0.0306	0.4	NOTTINGHAM (1999)
Lake URI, Switzerland, April, 1992 artificially induces rockfall	0.016	0.3 Field measurements and comparison with physical model results	MULLER (1994)

V is Volume of the Slide (in millions of m^3). H is the Maximum Height of the Resulting Tsunami (in m).

Since the Lituya Bay tsunami could have been due to a rock fall and not due to a submarine slide, regression was made with and without its inclusion. The difference in the results was not significant.

4. Model Results

Table 2 summarizes the results of some of the numerical simulations reported in the literature. Again it should be pointed out that this is an incomplete list.

Some of the above models are based on pioneering work by JIANG and LEBLOND (1992, 1993 and 1994). Even though the mathematics in these models is quite satisfactory, because of the somewhat idealistic geology that was inherent in such models, the results could sometimes be confusing and cannot be considered predictive for real events.

In recent years geotechnical engineers made good progress in more reliable mass failure prediction than was possible before. In the coming decade or so when there is more confidence in such predictions, undoubtedly the accuracy of tsunami simulations will also improve.

5. Discussion of Results

Figure 1 summarizes the results. A regression line was fitted making use of observational data alone. The results of the numerical simulations are plotted on the same diagrams. Based on this regression the following relationships are obtained.

$$H = 0.3945\, V \tag{1}$$

or

Table 2

Results of numerical simulations of landslide generated Tsunamis

V	H	Source and Comments
750	10.5	KULIKOV *et al.* (1999)
600	10.0	STREIM and MILOH (1976) Analytical Model
230	4.5	KULIKOV *et al.* (1999)
20	0.5	RUBINO *et al.* (1994) Their diagrams and numbers are hard to read, even with a magnifying glass. Our reading of the value for H could be wrong. They refer to slides with $V = 300$ as small.
1.25	4.0	KULIKOV *et al.* (1999)
0.8	6.5	RABINOVICH *et al.* (1999)

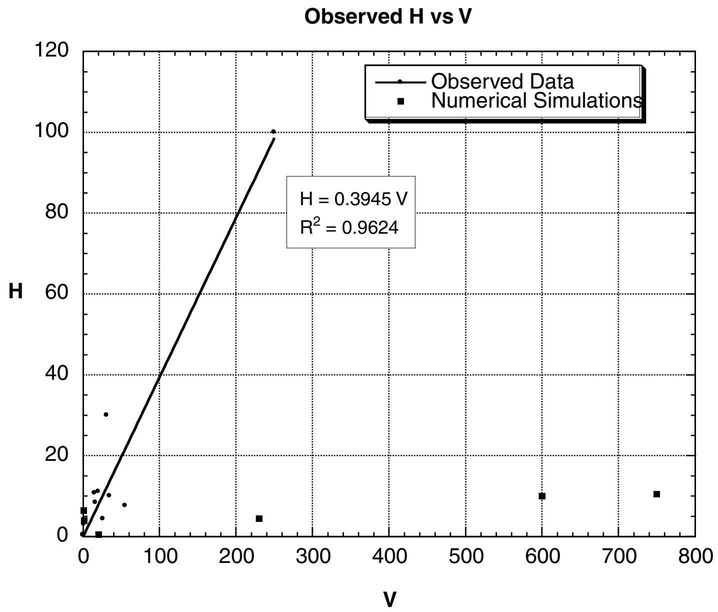

Figure 1
Observed maximum height of the tsunami (H in m) versus volume of the slide (V in millions of m^3).

$$V = 2.3994\,H, \tag{2}$$

where V is the volume of the submarine landslide in millions of cubic meters and H is the maximum amplitude of the resulting tsunami waves in meters. For example: $V = 10$ gives $H \approx 4$.

It is not clear why there is such poor agreement between observations and the results of some numerical simulations. However, it should be pointed out that all numerical simulations do not explicitly use the volume of the slide as one of the input parameters and quite accurate tsunami simulations have been made (WATTS, 1998; RAICHLEN *et al.*, 1996; and HEINRICH 1992). Since the aim of the present study is limited to finding a relationship between the volume of the slide and height of the resulting tsunami, no comparison was made with the results of the above models.

In particular, the work of Watts makes use of scaling which is deterministic and somewhat novel in tsunami research. In a sense, these models offer more detail in exchange for more parameters, some of which have limited availability at this time. However, with the increased interest in recent years in submarine landslides-generated tsunamis, there are good prospects for obtaining better information on the various parameters identified in the above studies.

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