GRAIN-SIZE DISTRIBUTIONS OF TSUNAMI SEDIMENTS

A Senior Scholars Thesis

by

SARAH CATHARINE SPENCER

Submitted to the Office of Undergraduate Research of
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

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Approved by:

Research Advisor: Robert Weiss
Associate Dean for Undergraduate Research: Sumana Datta

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ABSTRACT

Grain-size Distributions of Tsunami Sediments. (April 2011)

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Tsunami deposits indicate that suspended load transport is the main mechanism of movement throughout a tsunami event. Recent studies have touched on whether bed load transport is also occurring, but not seen in deposits due to the high energy nature of tsunamis. By implementing the use of simulation and modeling the tsunami depositional process may be fully understood. The program Python with PyLab was used to form distributions and calculate descriptive parameters with grain-size data from two past tsunamis, Chile 2010 and Peru 2008. The grain-size of the sediment from each tsunami was measured by two common techniques: sieving and digital particle counter. To interpret this real tsunami data, numerical and analytical analysis were used to simulate tsunamis through the use of the Analytical Tsunami Deposit Model (ATDM). Both the real world and simulated data were compared to each other and determined suspend load and bed load transport were occurring simultaneously during a tsunami event. Further research between the ATDM and present day tsunamis will allow a more finite understanding of tsunami sedimentation.

ACKNOWLEDGMENTS

I would like to thank Dr. Robert Weiss for providing me with this project and being a constant resource throughout its duration. I would also like to thank the Undergraduate Research Scholar Program for the guidance and support they have given me as a scholar.

NOMENCLATURE

ATDM	Analytical Tsunami Deposit Model

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CHAPTER I

INTRODUCTION

Tsunamis are high-energy events that displace a large volume of water in a series of waves. After the fact, the tsunamis leave behind a deposit that shows where the water first reached a specific point on land. Such deposits can be referred to as event deposits, which are episodic deposits of short-duration, unusual or high-energy processes relative to deposits of everyday normal conditions [Bourgeois, 2008].

For a tsunami event to take place, it has to be triggered by a mechanism such as an earthquake, volcanic eruption, or landslide. When these waves hit land they can cause monumental damage to the coastline and take many lives. We are then left with the task of understanding a tsunami event through evaluating the sediments that have been deposited on land. These deposits are the key to fully understanding past and future tsunamis. Recently, tsunami research has become more prominent within the geosciences due to the 2004 Indian Ocean tsunami. This particular tsunami opened a wider range in which to study tsunamis, as it affected a lower latitude coastline than seen in past tsunamis with similar magnitudes. It caused more than 225,000 deaths as well as impacting the coastal environment throughout the Indian Ocean [Huntington et al., 2007]. This event caused a flux of interest in tsunamis, and generated a increasingly important, revitalized focus of study for geoscientists.

This thesis follows the style of the journal of Coastal Engineering.

Literature overview

Current research has significantly increased our knowledge of tsunamis. There are various ways to study tsunamis, and many recent projects have chosen to focus on a tsunami's sediment. One such research group has used a sediment transport model, known as the TsuSedMod, to estimate flow parameters of tsunamis [Spiske et al., 2010]. This model estimates local tsunami flow speed through determining the velocity needed to suspend sediment volumes of a certain grain-size. For data this experiment uses two recent tsunamis (2004 Sumatra and 2006 Java) to compare and estimate the flow parameters. To calculate the grain-size of the sediment the three common techniques of measurement were used: sieving, digital particle measurement, and a settling tube. In this instance, a settling tube yielded the most effective and accurate way to measure grain-size. From the analysis of the data, the TsuSedMod determined only a minimum flow speed. No other flow speed was determined because factors, such as not accounting for backwash or successive waves, could have affected the outcome. As well, many parameters used to quantify the model are sensitive such as; the grain shape, thickness of sediment, and grading. The TsuSedMod is a excellent recent example of the use of modeling to understand the geologic history of a tsunami. In the end, it was found that by using the TsuSedMod reasonable estimates of the magnitude and frequency of events along a stretch of coast could be made. As well, it solidified the notion that modeling is an effective way to evaluate tsunamis.

Another relevant study evaluated the composition of the sediment of tsunami deposits [Jagodzinski et al., 2008]. In this experiment, heavy mineral assemblages effectiveness as indicators of the type of tsunami deposited was evaluated. Essentially, if it is possible to determine the magnitude of a tsunami through the weight of its sediment. The study questions the belief that beach sediment is transported as a bed load and tsunami sediment is transported as a suspended load. These scientists propose that tsunami sediment is transported as bed load and suspended load. Since there is a focus on heavy mineral assemblages, it is suggested that the presence or absence of mica minerals indicates if suspended load is occurring with bed load or as its own mechanism. Mica minerals are relatively light, therefore there presence is evidence for only suspended load transport. If there are no mica minerals, the tsunami will have also experienced bed load transport, as the composition of the sediment is significantly heavier. It was determined that the transport mechanisms used by tsunamis vary greatly. With a clearer understanding of a tsunami's transport mechanisms, the field of tsunami geology will be able to take a significant step forward.

Numerical and analytical modeling

Computer modeling is a vivid part of tsunami studies. The simulation of near-shore hydrodynamics has been improving since the mid 1990's. However, the use of this technique with processes such as sediment erosion, transport, and deposition is cutting edge. By modeling what has occurred, a greater knowledge of past tsunami events can be determined. Which in turn will allow future tsunamis to be evaluated to a greater extent. Through the use of models an entire depositional process can be seen. Whereas in the real world, the deposits that get left behind are all that we can learn from. Therefore, there are many processes we may not know happened as they did not leave any evidence behind. This is where modeling comes in. An entire tsunami event can be seen from start to finish, allowing each moment to be visualized. There is a margin of error within this type of modeling, as with any experimental technique. But the studies that have been done with modeling add significant, factual insight to our current knowledge of past tsunami events.

When analyzing a depositional process, the before, during, and after are all important parts of the event. The key to understanding this with tsunamis is to look at there physical makeup, also thought of as the sediment. Sediment is constantly being reworked throughout a tsunami event, and the deposit seen after is a factor of the tsunamis magnitude. By focusing on the sediment, and in this case analyzing the grain-size distribution throughout an event, we can potentially model events of similar magnitudes to those seen in real life. There is an importance both to evaluating tsunami hazard and to reconstructing geologic history [Bourgeois, 2008]. And this analysis can contribute to knowledge of the large-scale picture of high-impact events sediment deposition.

Descriptive parameters

Interpreting data can be a difficult task. To fully realize what you are looking at, statistical parameters will commonly be used to describe the results. One of such parameter is the mean, the average of a group of numbers. This is calculated by finding the sum of a group of numbers and dividing this by the number of numbers in the set. It is also be defined by the following equation:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{1}$$

Another commonly seen parameter is the standard deviation, which describes the variation of the mean. In other words, it shows how spread out the data is from the mean. This allows a general sense of how many outliers there are in a data set. It also shows how far from the mean they are. The standard deviation is defined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{2}$$

This is a basic statistical measurement that is the premise for computing the skew and kurtosis of a data set. The skew is the measure of the symmetry, or lack there of, of a distribution. It is defined as

$$\beta = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^3}{(n-1)\sigma^3} \tag{3}$$

The kurtosis is also based off a data sets standard deviation, however it measures how peaked or flat the distribution is to the normal. This is determined through the following equation

$$\delta = \frac{\sum_{i=1}^{n} (x_i - \bar{x})^4}{(n-1)\sigma^4} \tag{4}$$

Grain-size measurement

When referring to grain-size, the diameter of said grain is being measured. There are three different methods to measure grain-size, through the use of a settling tube, a digital particle counter, or sieving. The difference in the results yielded by each method can be substantially different. Therefore, it is important to understand each method, to determine which is most effective when measuring tsunami sediment.

A settling tube measures the grain-size indirectly, by recording the rate at which sediment falls through a column of water and settles on the bottom of a tube [Prothero and Schwab, 2008]. The digital particle counter, also known as camsizer, takes snapshot images of a single particle. The size of the grain is determined from the averaging of these images. A technical issue that occurs with this method is the camera may not take a complete 360 degree photo of the particle. In other words, error can occur from the camera not fully grasping the 3D size and scope of the particle. Sieving is the simplest method of grain-size measurement. The sediment is shaken through a nest of sieves until the amount retained is constant in each nest. After this, the sediment contained within each nest is weighed. This weight is then equated against the total amount of sediment. Even though all three of these methods produce some error, they are very effective ways to measure grain-size. When choosing which method to use, the method that is most readily available is used.

Grain-size class

The units used to define grain-size are either millimeters or phi units. Both units of measurement have scales that classify every grain-size to a specific group; such as mud, sand, or gravel sized particles. When grain-size is denoted geometrically, in millimeters, grain-size classification is based on the Udden-Wentworth scale. Whereas the phi scale is based on a logarithmic unit of measurement. Mathematically, this can be expressed as the following equation:

$$\phi = -log_2 d \tag{5}$$

As this equation shows, both of these scales are interchangeable. Each class has fixed boundaries for its respective class size of grains. These classes include, but are not exclusive to; boulder, cobble, pebble, coarse sand, fine sand, silt, and clay. Figure 1 [IODP, 2011] shows how the grain-size units are split into different classes:

Millimeters		µm	Phi (ϕ)	Wentworth size class	
			-20		
	4096		-12	Boulder (-8 to -12ϕ)	
	1024		-10		
	256		-8	Pebble (-6 to -8ϕ)	
	64		-6		
	16		-4	Pebble (-2 to -6ϕ)	Gravel
	4		-2		
	3.36		-1.75		
	2.83		-1.50	Gravel	
	2.38		-1.25		
	2.00		-1.00		
	1.68		-0.75		
	1.41		-0.50	Very coarse sand	
	1.19		-0.25		
	1.00		-0.00		
	0.84		0.25		
	0.71		0.50	Coarse sand	
	0.59		0.75		
1/2	0.50	500	1.00		
	0.42	420	1.25		
	0.35	350	1.50	Medium sand	Sand
	0.30	300	1.75		
1/4	0.25	250	2.00		
	0.210	210	2.25		
	0.177	177	2.50	Fine sand	
	0.149	149	2.75		
1/8	0.125	125	3.00		
	0.105	105	3.25		
	0.088	88	3.50	Very fine sand	
	0.074	74	3.75		
1/16	0.0625	63	4.00		
	0.0530	53	4.25		
	0.0440	44	4.50	Coarse silt	
	0.0370	37	4.75		
1/32	0.0310	31	5	Medium silt	
1/64	0.0156	15.6	6	Fine silt	
1/128	0.0078	7.8	7	Very fine silt	
1/256	0.0039	3.9	8		
	0.0020	2.0	9		Mud
	0.00098	0.98	10		
	0.00049	0.49	11	Clay	
	0.00024	0.24	12		
	0.00012	0.12	13		
	0.00006	0.06	14		

Fig. 1. Udden-Wentworth grain-size scale with millimeter to phi conversion chart.

Sediment transport

There are two ways to move sediment once it has been lifted into a flow, bed load and suspended load transport (Figure 2 [Prothero and Schwab, 2008]). Bed load transport involves traction load and saltation load transport. Some clasts are moved by traction, which involves rolling or dragging along the base of the moving fluid. Parts of the sediment are also moved by saltation, where clasts abruptly leave the bottom and are temporarily suspended. While in this suspension the sediment hops, skips, and jumps downcurrent in irregular patterns. Some saltating grains may hit other grains and cause them to be suspended and saltate as well. Both traction load and saltation load combined are known as bedload transport.

Suspended load transport is when clasts are in suspension, where the float continually throughout a moving fluid. Eventually some of the grains will settle out, while others will remain in suspension until there is no more movement of fluid.

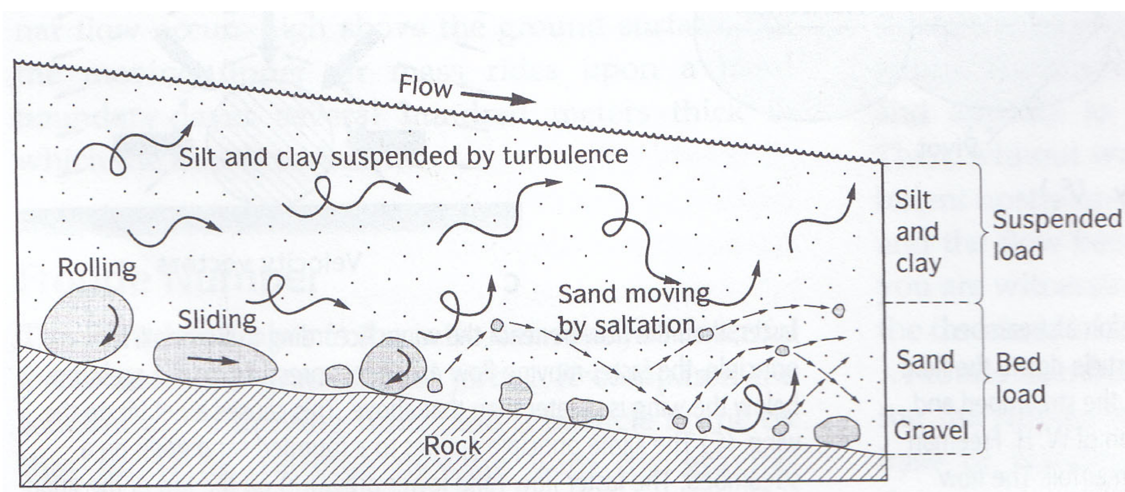

Fig. 2. Bed load and suspended load transport.

When analyzing a tsunami event, it is important to remember that sediment is being moved by a great force of water. From the deposits that a tsunami leaves behind, only suspended load transport is indicated. However, recent studies suggest that bed load transport may be occurring as well. The lack of evidence for this in nature is that the tsunami event erases all bed load deposits. Examining the transport mechanisms of a tsunami is essential to understanding tsunami events as a whole. First, we must be able to distinguish a (onshore) tsunami deposit from an onshore storm deposit [Bourgeois, 2008]. Storm deposits are distinguished by bedload transport with wedge-like deposits, whereas tsunamis exhibit suspended load transport and sheetlike deposits (Figure 3 [Bourgeois, 2008]). This is where modeling comes in, as a tsunamis entire depositional process can be modeled based on what it leaves behind.

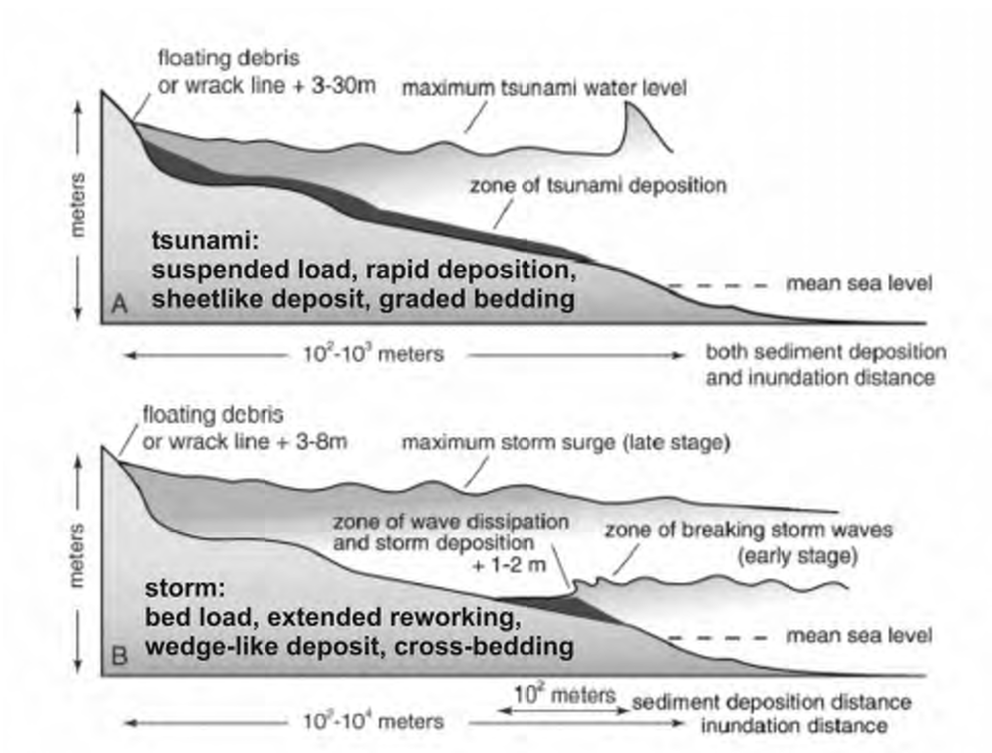

Fig. 3. Summary comparison of sand deposited by a typical tsunami and a typical storm surge, on a coastal profile.

CHAPTER II

METHODS

Data acquisition

Of the three methods to measure grain-size only a digital particle counter and sieving were used. A settling tube was not available for use. To begin, grain-size data was obtained from Dr. Michaela Spiske of Westfalische Wilhelms - University Munster (Germany). Dr. Spiske measured the tsunami sediment with a digital particle counter, also known as cam-sizer. Three different data sets were provided, one from the 2008 Peru tsunami and two from separate locations of the 2010 Chile tsunami. The organization of these data sets places every grain in a class based on its grain-size. The grain-size ranges from 0.015 millimeters to 30 millimeters. Within each class, the set of grains are evaluated numerically by count, volume, and ratio. The particular event the sediment is measured from is not a factor in the analysis of this data. As, each grain-size distribution is being thought of solely on the size of the sediment against an arbitrary factor. Therefore the given data from each tsunami can be equally weighted against each other.

Sieving was the second method used to measure the grain-size of tsunami sediment. The sediment measured is from the 2004 Indian Ocean tsunami. First, a nest of sieves, in this case five, each with a different screen size were chosen. In this study, the five screen sizes are .0394 mm, .0331 mm, .0197 mm, .0098 mm, to .0049 mm. The five sieves were stacked with the top having the largest screen size and the bottom the smallest. Then the sediment is placed at the top of the sieve, in other words resting on the .0394 mm screen. Next, the stack of sieves is placed in a mechanical vibratory sieving machine. The machine vibrates the sediment in horizontal and vertical movements. After a specified amount of time, the machine has separated the sediment by particle size throughout the mesh screens. The sediment that is left laying on each respective screen is then weighed. This value is representative of a grain-size slightly above and below the screens it is in between. Each screen's weight is then equated as its part of the total sediment. Distribution curves can now be formed.

Software

To formulate distribution curves, the programming language Python with PyLab was the system used. Python is a fast, easy to learn programming tool that is free to use and distribute. These qualities make Python ideal for this type of modeling. Especially since, the output is of high quality and easy to place into scholarly papers.

Grain-size distribution

To know what all the collected data tells us, grain-size distributions for each tsunami need to be arranged. With the digital particle counter data, each tsunamis grain-size was evaluated against the arbitrary value T. The resulting curve shows the increase and drop of the grain-size within the tsunami. By knowing the classification of grain-size, such as the size of coarse grained sand is 0.5-1 mm, you can conclude how fine grained or coarse grained the tsunami event was. This sheds light on the type of sediment transport. Coarser grained sediment indicates bed load transport, as typically suspended load transport can only carry fine grained sediment. Descriptive parameters were also calculated from these distribution curves. The mean, standard deviation, skew, and kurtosis are parameters that describe the shape of the curve. By comparing each curve with the use of these parameters, the differences between each event is seen. With the sieved data, the results are shown as a bar graph, not a curve. This is because the grain-sizes are calculated as a weight and therefore analyzed as a percent of the whole. The results from sieving show the change in grain-size throughout the tsunami event as effectively as those from the digital particle counter.

ATDM

The next step of this study is to simulate tsunami events. The ATDM is based on the assumption that the fluid involved in a tsunami event carries all available sediment at all times. The fluid and bottom sediments are controlled by the shear velocity and its role within the Rouse equation. From this basis of fluid mechanics, the model will capably demonstrate the interaction between fluid and sediment during a tsunami event.

Shear velocity, u_*, in a fluid system is described by the law of the wall [Winterwerp and van Kesteren, 2004]:

$$\frac{u(z)}{u_*} = \frac{1}{\kappa} log \left[\frac{z}{z_o} \right] \tag{6}$$

The shear velocity is dependent on the fluid velocity, u, and the roughness length, z_o. In this equation, z is the vertical coordinate and κ is the von Karman constant. Therefore, a proportion between the roughness length and height of saltation is made. This denotes the profile of the tsunami.

The Rouse equation addresses the time dependent concentration of a fluid flow. It is an analytical solution that assumes steady flow and incorporates turbulent fluxes due to mixing. Classically, it is denoted as the following equation [Kranck and Milligan, 1985]:

$$\frac{C(z)}{C_o} = \left(\frac{\eta - z}{\eta - z_o} \frac{z_o}{z} \right)^x \tag{7}$$

Here C_o is the reference concentration level at z_o. x is the Rouse number, which is equivalent to [Kranck and Milligan, 1985]:

$$x = \frac{w_s}{\kappa u_*} \tag{8}$$

This dimensionless number represents the relationship between the gravitational settling of grains, w_s, and turbulent fluctuations, κu_*. Past studies have determined that when $x \geq 2.5$ all grains move through bed load transport. When $x \leq 0.8$ all grains move through suspended load transport. This may vary slightly. These values give boundaries so an analytical application can determine the type of transport occurring. If this calculation is made, it can be applied to predict the formation of bed forms. Figure 4 shows a visualization of this change in grain-size over time due to the calculated Rouse number. Here it is seen that with a larger Rouse number, such as 2.0 or greater, the grain-size is medium to coarse grained. Which is evident of bed-load transport. Therefore, by having the reference concentration (C_o), the total roughness length (z_o), and the depth-averaged shear velocity concentration ($\frac{w_s}{\kappa u_*}$) profiles can be computed and solved. This is the premise to how the ATDM functions.

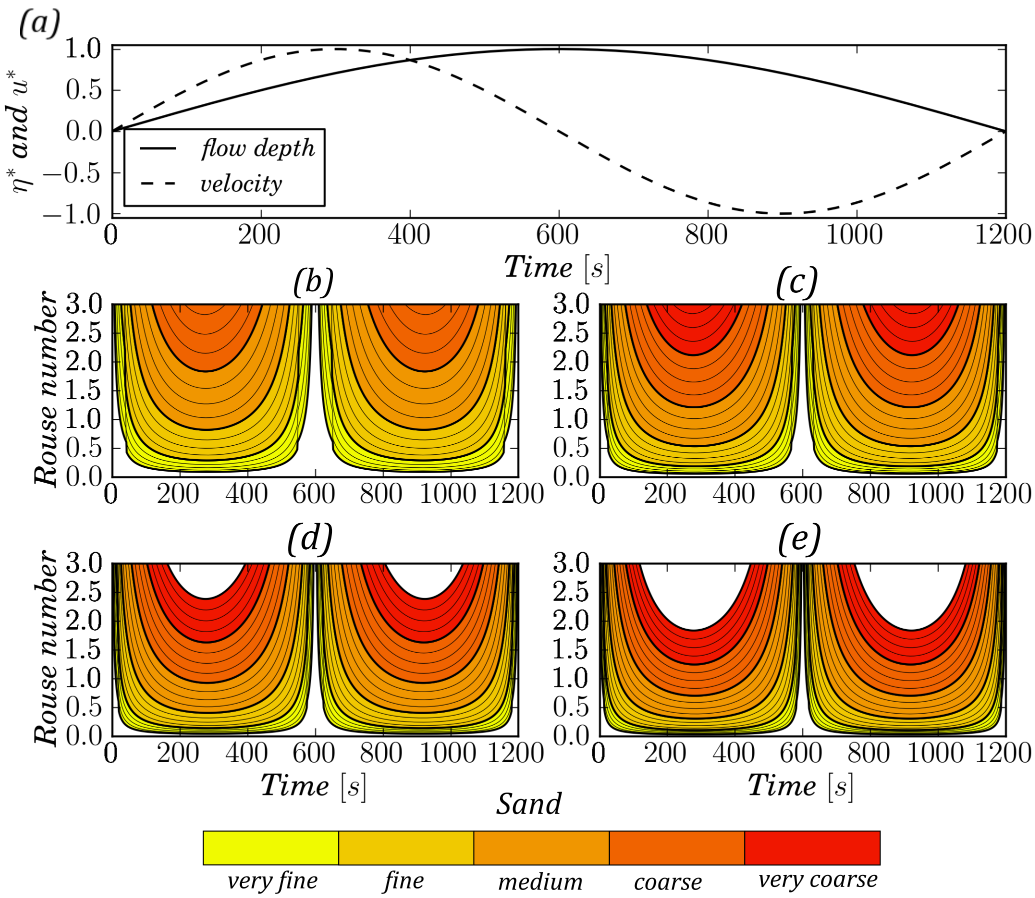

Fig. 4. Panel (a) gives the series of the flow depth and flow speed. (b)- (e) shows the Rouse number for the grain-size classes very fine, fine, medium, coarse, and very coarse sand.

Probability of stay

The amount of evidence left after a tsunami event is a major contributing factor to our knowledge of the event. Therefore, the type of sediment deposited and the probability that it will stay determines how we evaluate the data. Fortunately, this can be mathematically computed which gives us the ability to model.

The Rouse equation assumes flow to be steady and in equilibrium. When looking at the probability of stay, within a time interval Δt, the flow is steady. If there are l time steps, the change in concentration, and therefore erosion and deposition, can be observed. In this context, the Rouse equation is solved for each grain-size class k with $1 \leq k \leq n$, the total number of grain-size classes. The grain-size distribution for the fraction of the flow that leaves or enters the can be found by the following equation:

$$p'(k) = \Delta C_{T,k} \tag{9}$$

$\Delta C_{T,k}$ is defined as the concentration that enters or leaves the flow of class k. By assuming a normal distribution of stresses, the probability of stay can be derived as the following (Gessler):

$$q\left(\frac{\tau_c}{\tau}\right) = \frac{1}{2}\left[1 + erf\left(\frac{\left(\frac{\tau_c}{\tau}\right) - 1}{\sqrt{2}}\right)\right] \tag{10}$$

The probability distribution accounts for error and defines a probability q = 0.5 for a stress ratio of $\left(\frac{\tau_c}{\tau}\right)$=1. This allows the cumulative grain-size distribution p_s to be computed:

$$p(s) = qp'(k) \tag{11}$$

This model incorporates probability of stay with the Rouse equation to determine the grain-size that is entering and leaving the flow. This, along with calculating the shear velocity and Rouse number, allows the ATDM to simulate a tsunami.

CHAPTER III

RESULTS

Three graphically different types of grain-size distributions representing tsunami sediment were formulated. Each is unique in the method of grain-size measurement and graphic representation. Figure 5 is the distributions from the data measured by the digital particle counter.

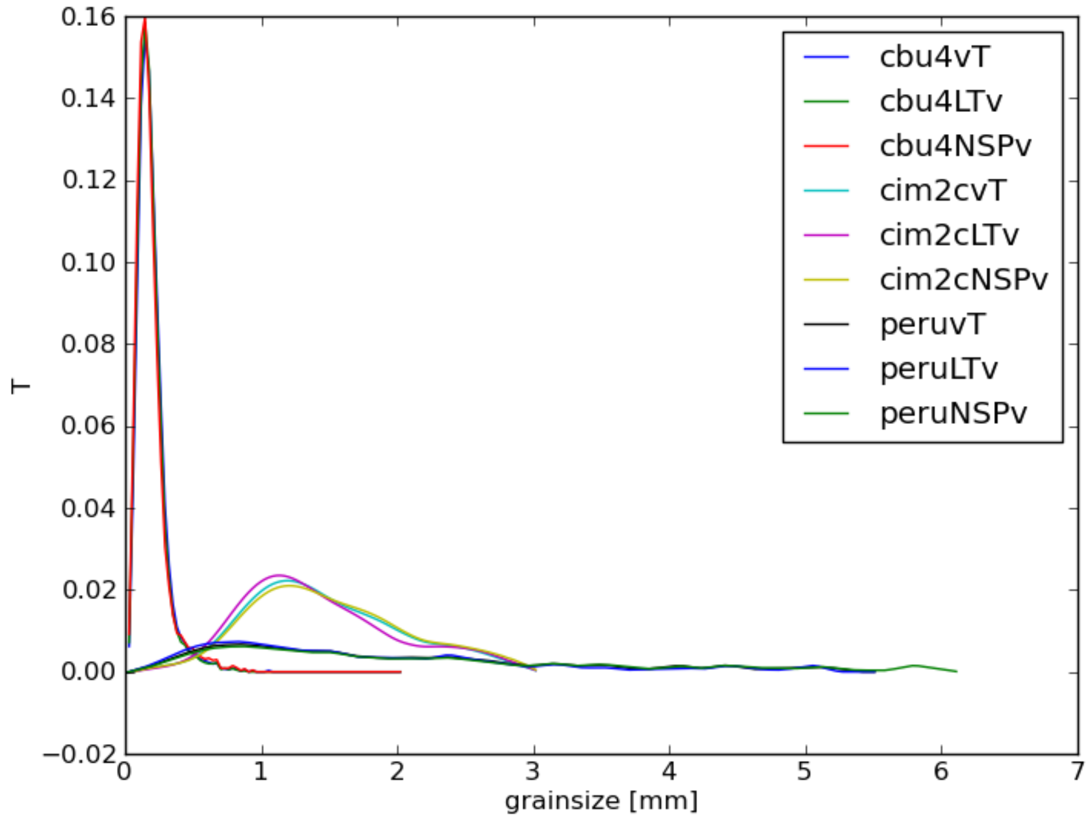

Fig. 5. Grain-size distributions from Chile 2010 and Peru 2008.

Insight on the shape of the curves seen in Figure 5 is given by the statistical parameters computed for each of the nine distributions. These statistics, the mean, standard deviation, skew and kurtosis, show both similarities and differences of the curves (Figure 6).

	mean	standard deviation	skew	kurtosis
cbu4vT	41.99105953	343.7488076	8.428780096	70.01470588
cim2cvT	38.39872743	385.9209818	10.2483905	104.0098039
peruvT	77.29916403	1574.708241	20.46966578	418.0024038
cbu4LTv	34.50698872	282.4824227	8.428780096	70.01470588
cim2cLTv	34.66362066	348.3818193	10.2483905	104
peruLTv	76.26024569	1474.808206	19.44242801	377.0026667
cbu4NSPv	21.71124593	177.7334266	8.428780096	70.01470588
cim2cNSPv	24.10191529	242.2328925	10.2483905	104.0098039
peruNSPv	52.38040728	1012.992468	19.44242801	377.0026667

Fig. 6. Statistics for Chile 2010 and Peru 2008.

Figure 7 represents the bar graph formed from the data measured by sieving. Remember, the bars are the concentration of the sediment at its particular screen size.

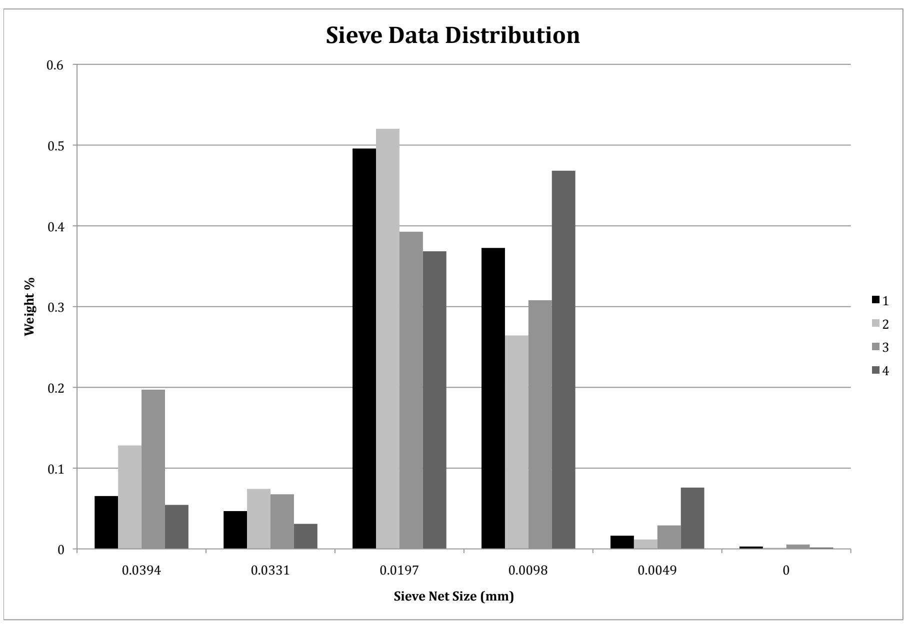

Fig. 7. Sieve distributions.

Figures 8 and 9 are two selected images from the simulated tsunami event created by the ATDM. The model first calculates the grain-size distribution that is the basis for simulation. This is the gray curve seen as the background. The yellow curves are the grain-size distribution of the tsunami at a selected moment of time. These two images were chosen as there is a significant change in sedimentation rate that occurs between the two points in time.

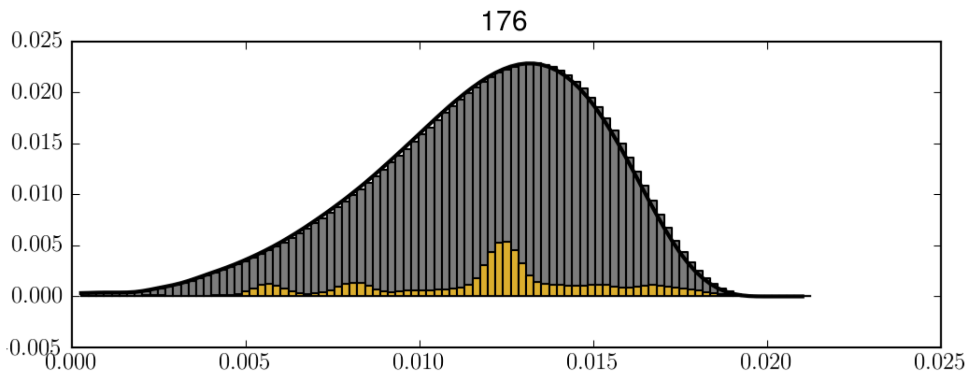

Fig. 8. 176

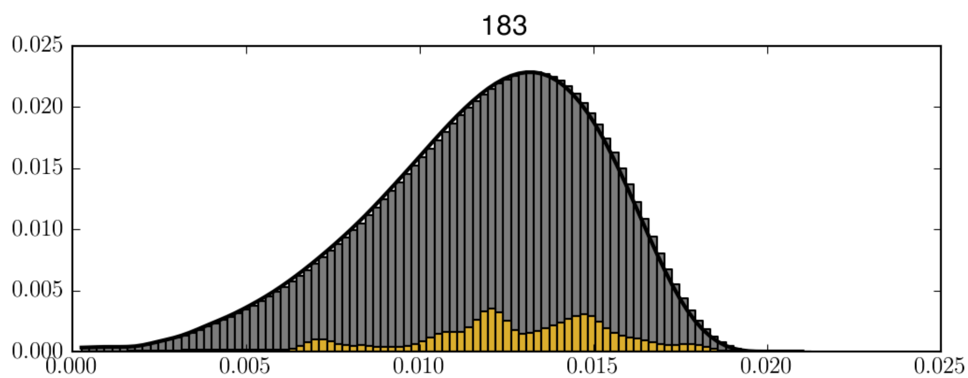

Fig. 9. 183

CHAPTER IV

ANALYSIS AND SUMMARY

The grain-size distributions for the sediment measured by the digital particle counter shows the different ways sediment is carried in tsunami events. Two of these curves are from the same tsunami, Chile 2010. The cbu4 curve is mainly composed of very fine grained sediment while the other, cim2c, holds a much more even distribution of sediment with the high concentration from a medium to coarse grain-size. The Peru 2008 tsunami has the most even distribution of grain-size and only experiences a slightly higher concentration with medium grained sediment. These trends are mirrored in the statistical parameters calculated for each tsunami event. By finding these values, the curves shapes are validated. This is important as in computer modeling the accuracy of the output is hard to determine. The sieve distribution shows that each tsunami event weighed has a approximate size concentration of 0.0197 and 0.0098 mm, also known as very fine sand. This is most similar to the cbu4 Chile 2010 tsunami. If a trend line was emplaced on this bar chart a distribution similar to those in Figure 5 will be seen.

The mathematical premise of the ATDM is the flow depth is a governing factor. For this study, a average tsunami flow depth of 4.0 meters was choosen [Bahlburg and Weiss, 2006]. The results form a series of images that show how the grain-size changes throughout a tsunami event. In these images a ”jump” in the sedimentation rate is seen at approximately three quarters after the beginning of the event. Figure 8 shows a uneven, peaky curve versus Figure 9 that has a more even distribution. At this change, the sedimentation rate changes from sporadic to constant. Part of this is due to a larger grain-size at the end of the event. As well, it shows the mechanisms of sediment transport are more complex then simply suspended load. The logical explanation is that bed load transport is occurring simultaneously with suspended load.

The ATDM enables us to see how the grain-size changes over time whereas simply measuring sediment only shows us the distribution of sediment after an event. By taking grain-size distributions from real events and using the ATDM, how the distribution was formed can be modeled. As with anything, there will be error due to the completeness of preservation after tsunami events. All three methods used in this study show that tsunamis are fine to coarse grained events. Through the ATDM it is seen that more than suspended load transport is occurring due to a sudden change in grain-size and sedimentation rate throughout an entire tsunami depositional process. By further research with the ATDM and comparing it to this real data, validation that suspended and bed load transport are occurring can be made.

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