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'HANGING TEN': MEASURING BIG WAVE INTENSITIES

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ABSTRACT

The entire world is still feeling the effects of the devastating 2011 Honshu earthquake and tsunami. The Cascadia subduction zone, spanning over 800 miles from Vancouver Island to northern California, is soon expected to complete its 500-year quake cycle with a magnitude 8+ tsunamigenic earthquake. Much attention is being given to planning for this potential disaster and its collateral impacts from landslides, fires, hazardous material spills and infrastructure damages. The devastating impact of future tsunami events in this region and elsewhere, may result in millions of deaths and billions of dollars in damages. Over the years numerous attempts have been made to quantify tsunami severity but none of the devised scales have been completely satisfactory. The present study reviews and discusses the scales of magnitude and intensity that have been developed to describe the severity of tsunami events both qualitatively and quantitatively. Furthermore, it defines a new quantitative scaling measure of tsunami severity which is an improvement over widely reported current scales, by comparing the 'Top Ten Lists' of devastating tsunami as calculated by each of the scales.

Keywords: *tsunami severity, wave intensities, tsunami magnitude, top ten tsunamis.*

1. INTRODUCTION

In surfing, 'hanging ten' is the term used to describe a surfer's position on the surfboard, in such a way that the back of it is covered by the wave and the rider is free to walk to the front and hang all ten toes over the nose of the board (see the photograph in APPENDIX I). Of course, this cannot be done with tsunami waves which simply cannot be surfed. In this paper, we have borrowed the term "hanging ten" to identify the top ten most devastating tsunamis, based on our newly defined scale of intensity.

The most severe tsunamis are generated from major and great earthquakes near zones of subduction. At boundaries of subduction, the colliding tectonic plates remain locked for long periods of time until a threshold limit of elastic deformation is reached, at which time the stress is released by an earthquake and a tsunami is generated by the vertical and horizontal crustal movements of the ocean floor. The 11 March 2011 tsunami in Honshu, Japan was such a long-overdue extreme event, generated by a great earthquake with magnitude 9.0+ (NGDC, 2011). The tsunami was primarily responsible for most of the great destruction and the deaths of well over 15,000 people. Collateral tsunami damage included the spread of debris across the Pacific Ocean and the destruction of the Fukushima-Daichi nuclear plant, which released large quantities of radioactive Cesium-137 and other radionuclides – subsequently uptaken by migratory fish such as tuna. We have studied extensively this particular tsunami and its effect on the Japanese prefectures as they relate to the distribution of extreme tsunami wave heights (Potter, October, 2011 in review).

The 26 December 2004 mega-tsunami generated along the Island of Sumatra and in the Andaman Sea, was another event that devastated many countries bordering the Indian Ocean Basin and killed more than a quarter of a million people. It was triggered by an earthquake of magnitude 9.1 resulting when the India plate suddenly subducted beneath the Burma microplate. To the list of other historical mega-tsunamis we must also include the one generated by the magnitude 9.2, 1964 Good Friday earthquake in Alaska which affected many other areas in the Pacific and the Hawaiian Islands. Even Vancouver Island which was over 1,100 miles away from the source region, experienced millions of dollars in damages from this tsunami. In addition to the major tsunami generated in the Gulf of Alaska, many more local, extremely destructive tsunamis were generated by this event in Prince William Sound and in the Valdez basin.

Presently, there are many more regions in the Pacific and elsewhere in the world where future destructive tsunamis can be expected. One such region is the Cascadia subduction zone off the US. Northwest coast where the Juan de Fuca and the North American plates collide. This seismic zone spans over 800 miles from Vancouver Island to Northern California. The recurrence interval for great quakes along this zone has been estimated to vary between 300 – 600 years. Earthquakes with magnitude 8 or greater have been estimated to occur on the average of about 500 years – the last one in 1700 A.D. Needless to say that much attention is being given to planning for this expected tsunami event and its collateral consequences, such as landslides, fires, hazardous material spills and building damages. The Cascadia Region Earthquake Workgroup (CREW, 2005) has concentrated on preparing this region with the intention of reducing the potential risk.

Ongoing research suggests that a rupture along the Cascadia zone would cause the sea floor to be raised by 20 feet or more, setting off powerful waves in the near field region. The first tsunami waves could hit coastal communities within 30 minutes or less -- too rapidly for the current warning system to respond adequately and save lives. Thus it is important to discover as much as possible about this expected tsunami hazard and engage in proactive behavior in planning, preparedness and in ascertaining as much as possible about the source region and the expected severity. Such efforts can only serve to improve the regional warning system and tsunami preparedness.

2. TSUNAMI MEASURES THEN AND NOW

In attempting to quantify tsunami severity for the purpose of comparing events, numerous attempts have been made over the years but for many reasons none have been completely satisfactory. Calculating the total power and energy for most tsunamis is very difficult today due to lack of ability in technology and resources to both measure and collect the needed vast amounts of data. The challenge continues to be in discovering the balance between the appropriateness and the availability of the statistical data to use in determining what exactly should be quantified. A thorough review of quantification of tsunami up to 2001 can be found in the literature (IMAMURA, 2001).

In 1956, the Iida magnitude scale (Iida, 1956) was developed to measure tsunami magnitude. It is defined as M= $\log 2H$, where H is the maximum wave height. Then in the 1970's, the Soloviev – Iida Intensity Scale was introduced as a variation on the magnitude scale where $I= 12+ \log 2H$. Subsequently in 1979, the Abe Magnitude Scale (Abe, 1979) for earthquake-generated tsunami appeared as $Mt=\log A+a\log R+D$, where A is the maximum amplitude of tsunami waves, R is the distance (km) from the earthquake epicenter to the tide station and a and D are constants which attempt to coincide with the Richter scale magnitude.

In 1980, Murty & Loomis developed the ML magnitude scale (LOOMIS, 1980), where $ML = 2(\log E - 19)$ and E is the total potential energy at time of generation of the tsunami, which involves calculating the elevation or subsidence and the area of the ocean bottom affected at the time of generation. The range of scale values lies in the interval [-4, 10]. This ML magnitude scale was tested on a partial list of tsunamigenic earthquake events prior to 1974 (LOOMIS, 1980), where it was mentioned that the values should be treated as strictly tentative at best since data estimates were often conflicting. In addition to the extreme difficulties in calculating potential energy of an event, this measure also does not take into consideration tsunami propagation effects like ocean floor topography and bathymetry, which do have great influence over the event. This measure is therefore not widely used or reported. Also, none of these magnitudes or intensities measured degree of impact or event effects. Instead, they all calculated a magnitude based on the physical parameter of wave height of the natural event measured at a particular location.

In the 1990's, Shuto developed the Shuto Intensity Scale (SHUTO, 1991), which combined magnitude and intensity for the purpose of predicting expected tsunami impact as a function of wave height. Shuto defined six grade intensities in the range 0 – 5 based on divisions of $i=\log 2H$. Finally, in 2001, Papadopoulos & Imamura introduced their Qualitative Intensity Scale (IMAMURA, 2001) based on Twelve Divisions (I-XII) arranged in order according to effects on humans, effects on objects and nature and damage to buildings. This scale is independent of the physical parameters that control the type and extent of effects in that it does not explicitly involve their measurements.

Currently, the NGDC reports tsunami magnitude and intensity using the Iida magnitude and the Soloviev intensity scales. The Abe Magnitude Scale is also occasionally reported for some earthquake-generated tsunamis. Each of these scales relies on wave height of the event as the determining statistic. The current tsunami warning system using DART gages for detection is triggered by a threshold wave height value (MILBURN, PMEL NO. 2836). The power, the energy flux (Zygmunt, 2008), the magnitude, the intensity (McIntyre, 2005), the velocity or wave speed and the underwater friction coefficients (Xu, 2007) of a tsunami are all determined by or at least in part by the maximum wave height of the tsunami.

3. A MISSING DETERMINING PHYSICAL PARAMETER

Every one of the quantitative measures widely reported to date uses maximum wave height measured at a particular location as its determining physical parameter. None of these measures have been satisfactory because as it turns out wave height is not the only determining factor in a devastating tsunami event. By taking a look at two major events, we can see there is something missing in these measures.

The Mt. St. Helens' volcano-generated tsunami of 1980 at Spirit Lake holds the record for the second highest wave since 1900. Its Iida magnitude is at 7.97, Soloviev intensity at 8.47, Shuto index of I = 5 and P&I index of XII. The 2004 Indonesian earthquake-generated tsunami has a waveheight only 20% that of Spirit Lake Tsunami, but it is the deadliest tsunami in recorded history - having killed many more than a quarter of a million people. Its Iida magnitude is at 5.67, the Soloviev intensity at 6.17, the Shuto index of I = 5 and the assigned P&I index is XII. A summary of these event statistics can be found in APPENDIX II. These Iida and Soloviev numbers accurately detect the 200 meter difference in the wave heights of these events. The Shuto and P&I indices do not distinguish between these events. But the overall power of these events was vastly different.

In general, the exact computation of the power of an event is difficult due to lack of ability in technology to measure and economics to collect all the data needed. In considering what we mean by tsunami power, we need to determine the energy delivered by the individual waves to the shoreline, as well as how much shoreline experiences the wave in the event. We define the power of a tsunami event as:

$$P\ tsunamievent = allwavesPwavefront * Dshorelin\square\square\ ,$$

where $Pwavefront$ is the power of a wave front per meter of shoreline and $Dshoreline$ is the distance in meters of shoreline affected by the wave. Now, $Pwavefront = Edensity \cdot C\ \ Js/m$ (watts per meter), where $Edensity = \rho water \cdot g \cdot H28\ kgs2$ (Joules per square meter) $=1{,}225H2\ kgm2$, and C is the celerity *or* wave front velocity measured in m/s. It's easy to see that the vast amount of data needed to compute these quantities exactly and uniformly would be very difficult to obtain considering economic and technological restraints.

However, we can develop an approximation to the power formula that will be useful in distinguishing such events. See APPENDIX III for a discussion on such an approximation and its use in calculating approximations for power of the Spirit Lake and Indonesian tsunami events. The Mt.

St. Helens tsunami delivered 1100 giga-watts of power to the shores of Spirit Lake. That's more than 500 times the peak power generation of the Hoover Dam. It is worth noting that the entire length of shoreline affected in the Indonesian tsunami is vast because its effects were felt around the world. Sri Lanka alone was hit by a total power of half a terawatt (0.5×1012) by the Indonesian tsunami. Half a terawatt could power about 5 billion 100-watt light bulbs at the same time. Half a terawatt is 3% of the annual world power consumption.

The Iida and Soloviev numbers accurately detect the 200 meter difference in the wave heights of these two events but fail to account for the extreme severity of the Indonesian event in comparison to the Spirit Lake event. The difference between them was the run-up values. A run-up occurs when the crest of the wave hits the shore, sea level rises and the momentum of wave motion results in some higher value of flooding inland. Run-up information is not accounted for in these magnitude and intensity measurements – only the wave heights. There may be quite a difference in the degree of severity of a tsunami and the resulting run-up values, depending on coastal topography and on wave energy focusing due to offshore refraction.

The Mt. St. Helens volcano-generated tsunami of 1980 at Spirit Lake holds the record for the second tallest wave since 1900 but had only two run-ups, while the 2004 Indonesian earthquake-generated tsunami in the Pacific Ocean had a wave height only 20% of that of Spirit Lake tsunami but had 1058 run-ups – the second highest number of run-ups in tsunami history! In addition to tall waves, the number of run-ups in an event turns out to also be a crucial factor in determining severity and devastation.

In APPENDIX V, we form the top ten lists of devastating tsunami (since 1900) by deaths in Table (i.) and by damages in Table (iii.), and compare those to the top ten by wave height and again by run-ups. Most entries in the list 'By Deaths' don't have significant wave heights. Instead they have vast numbers of run-ups, which further demonstrates the importance of considering large run-up quantities in measuring devastation.

Table (ii) shows the 'Wave height' list misses 80% of the most deadly tsunamis and underestimates the devastation in 100% of those it does manage to find. Table (iv) shows the 'Wave height' list misses 60% of most devastating tsunamis by damages and underestimates the devastation of 75% of those it manages to include. The 'Run-Ups' list in Table (v) finds 10% more devastating tsunami by deaths than the 'Wave-heights'. The 'Run-Ups' list in Table (vi) captures 60% of the devastation by damages in the Top 10 'By Damages' list versus 'Wave height', which captures 40%. The 'Run-Ups' list tends to overestimate damages in 75% of those it captures which contrasts the 100% underestimation of 'Wave heights'.

This trend continues when even more events are considered. For example, by comparing the top 25 events by wave height and deaths or damages, we find the 'Wave height' list coincides with only 24% of the 'By Deaths' list and 44% of the 'By Damages' list. Note that after the top 25, observed wave heights all fall short of 20 meters, and, after the top 50, they fall short of 11 meters. By comparing the top 50 events in the wave height and deaths lists, we find 42% coincidence. There are 39 reported events on the entire 'By Damages' list, and a comparison of this list with the 'By Wave height' produces 38% coincidence.

It is interesting to note that, in the 'By Deaths' list, 80% of events were caused by earthquakes and 20% by landslides. In the 'By Damages' list, 90% of events were caused by earthquakes and 10% by landslides. In contrast, in the 'Run-Ups' list, 90% of events were caused by earthquakes, while 10% resulted from a volcano; and, in the 'Wave heights' list, 40% resulted from an earthquake, while 30% were from landslides and the rest from volcanoes. From our analysis, we can see it is essential to include both height and run-up statistics in building models to help analyze certainty and severity of tsunami events.

4. A NEW MEASURE OF TSUNAMI SEVERITY

We now define a quantitative measure of tsunami severity which includes the run-up number statistic and show it in Section 5 to be a major improvement over current measures by comparing the most devastating tsunami as calculated by each measure with respect to deaths and damages. We want to be able to compare tsunami universally by degree of severity. The most severe storms have the largest wave heights and most run-ups (power behind them).

A natural way to associate the power of an event with a severity index is to compute the index using the determining variables in the power estimation. The maximum wave height observed in a tsunami event determines the maximum power per meter wave front of the event. If there are *N* run-ups and *H* is the maximum observed wave height in the event, we associate the power per meter wave front of the event with that of the tallest wave. Then we can further associate the power of a tsunami event with the product of run-ups and the measure of the tallest wave:

$$P\ tsunamievent \qquad N*H$$

A detailed description of this association can be found in Appendix IV. We define an index to capture tsunami devastation in magnitude and intensity.

Define the Log – Power (LP -) Index of a tsunami event as

$$\boldsymbol{LP} = \mathbf{log}\boldsymbol{N*H},$$

where *N* = number of event run-ups and *H* = maximum run-up height in the event. Values generally lie in the interval (-6, 6), and so it is straightforward to adjust the index (by a constant shift) to provide a correlation to the Shuto Intensity or P & I Qualitative index scales, which are partitioned according to maximum wave heights. The association described is very convenient for common use since the events are popularly and routinely reported by citing maximum wave height and run-ups experienced by the event (NGDC, 2011).

5. 'TOP TEN' LISTS OF DEVASTATING TSUNAMI

Table (vii) in APPENDIX V shows the Top 10 Most Severe Tsunami identified by the LP-Index. The first event on the LP-Index Top 10 List is the 2011 Honshu event, which is the costliest tsunami in recorded history and the second highest in death toll. The second event is the 2004

Indonesian tsunami, which is the deadliest tsunami in recorded history and the third highest in damages. The LP - Top 10 coincides with 50% of the ‘Wave height’ Top 10 list. Now 60% of those events on the LP - Top 10 but not on the ‘Wave height’ Top 10 list coincide with the ‘By Damages’ Top 10, while 20% coincide with the ‘By Deaths’ Top 10. So, entries appearing on the LP list that don’t coincide with those on the ‘By Wave height’ list are more severe than those with higher wave heights due to few or no deaths or damages reported.

The LP – Top 10 also coincides with 70% of the ‘Run-ups’ Top 10 list and of course includes all entries simultaneously on both ‘Run-Ups’ and ‘Wave height’ Top 10 lists. Now 20% of those events on the LP – Top 10 but not on the ‘Run – Ups’ Top 10 list coincide with both ‘By Deaths’ and ‘By Damages’ Top 10 lists. So, 67% of entries appearing on the LP list that don’t coincide with those on the ‘By Run-Ups’ list are more severe than those with more run-ups due to few or no deaths or damages reported. The only tsunami on the LP – Top 10 list that does not appear on one of the two ‘By Run-Ups’ or ‘By Wave height’ Top 10 lists is the 1933 Sanriku, Japan tsunami which had a 29 *m* wave height, 295 run-ups and 3,022 deaths. This event does appear sixth on the ‘By Deaths’ Top 10 list.

How accurately the LP-Index detects devastation by deaths and by damages can be found by comparing Tables (i), (iii.) and (vii). The Top 10 ‘By LP-Index’ coincides with 70% of the Top 10 ‘By Damages’ and 30% of the Top 10 ‘By Deaths’. This represents a 43% and a 34% improvement over current measures, respectively, because 40% of Top 10 by wave height made the Top 10 by damages, and 20% of the Top 10 by wave height made the Top 10 by deaths as shown in Section 4.

These LP – Index results are far more satisfactory than any of the magnitude or intensity scales widely reported today since those rely solely on the wave height statistic. This improvement trend continues when considering greater numbers of top events. For example, by comparing the top 25 events by LP-Index and deaths or damages, we find the LP-list coincides with 36% of the top ‘By Deaths’ and 56% of the top ‘By Damages’ lists. This represents a 34% and 22% improvement over the top 25 “By Wave height’ list in comparison with the top 25 ‘By Deaths’ and ‘By Damages’ lists, respectively. Again, note that after the top 25, observed wave heights all fall short of 20 meters, and, after the top 50, they fall short of 11 meters. By comparing the top 50 events by LP-Index and deaths, we find a 46% coincidence, an 18% improvement over considering wave heights alone. There are 39 reported events on the entire ‘By Damages’ list, and a comparison of this list with the ‘By LP-Index’ list produces 46% coincidence, a 12% improvement over considering wave heights alone.

Similar results are found for the Top 100 categories. A 58% coincidence in the Top 100 ‘By Deaths’ and ‘By LP-Index’ coincide. It is not surprising to note that there is over 70% coincidence in the Top 100 ‘By Wave height’ and the Top 100 ‘By LP-Index’ lists. It is also important to note 30 of the last 100 wave heights on the Top 100 ‘By Wave height’ list are fewer than 6 meters tall, 39 of 100 of these have recorded damages, and that 39 of these events also have fewer than 20 deaths. Comparing the Top 100 ‘By Wave height’ to the Top 100 list ‘By Deaths’ yields 54% coincidence, respectively. So, for these events which include many non-devastating and many incompletely reported storms, the LP-Index represents a 7% overall improvement in the ‘By Deaths’ category on the top 100 events.

Therefore the LP-Index makes a significant improvement over current measures with vast improvement seen in comparing current measures of the most severe events with respect to damages and deaths. It is clear that including the run-ups statistic in the computation of tsunami intensity and magnitude makes an important contribution and should therefore not be ignored. The LP-Index is very appropriate for common use because the events are popularly reported by citing maximum wave height and run-ups experienced in the event. Moreover, the LP-Index is independent of the cause of the tsunami event. The closer we can approximate the severity of tsunami events, the more capable we will be in comparing and contrasting their potential devastation. This will aid in planning for their arrival and predicting their severity, thereby enabling us to improve tsunami warning systems and protect our shores.

APPENDIX I. Hanging Ten

'Hanging ten' is when the surfer positions the surfboard in such a way that the back of it is covered by the wave, and the wave rider is free to walk to the front of the board and hang all ten toes over the nose of the board.

APPENDIX II. Measure Comparisons of Two Major Events

Measures	Spirit Lake Event	Indonesian Event
Maximum Waveheight (*m*)	250	50.9
Deaths	-	226898
Iida Magnitude	7.97	5.67
Soloviev Intensity	8.47	6.17
Shuto Index	5	5
P & I Index	XII	XII

Note: The Shuto and P & I Indices quoted here are the maximum value in each scale, representing the most completely devastating tsunami (Imamura, 2001).

APPENDIX III. Estimating Power

The power per meter wave front is the product of energy wave density and the celerity of the wave (wave speed). With seawater density measured as $\rho water=1000\ kg/m3$, h= depth below mean sea water level in meters, H=twice the wave height above mean sea water level (twice the amplitude), and the gravity constant $g=9.8m/s2$ (as in Figure 3), then the power per meter wave front is:

$Pwavefront=Edensity\cdot C\ \ Js/m$ (watts per meter), where $Edensity=\ \rho water\cdot g\cdot H28\ kgs2$ (Joules per square meter) $=1,225H2\ kgm2$, and C is the celerity *or* wave front velocity measured in m/s.

The maximum wave height observed in a tsunami event determines the maximum $Edensity$ of the event. The energy per meter of wavefront, $Ewavefront$, is the energy wave density per meter wavefront. To compute the total energy of a single tsunami wave affecting a region, multiply the energy per meter wavefront by the meters of shoreline affected. To compute the total energy of all tsunami waves in an event affecting a region, sum the energies per wave over all waves in the event. This describes the energy per meter wave front of the tsunami event at one region, but often many regions are affected by the same event. A sum over all regions is needed.

The 2004 Indonesia tsunami had over 950 regions reporting event observations around the globe, reaching areas ranging from France to New Zealand. The regions experiencing and recording a wave from a tsunami event coincide with the recorded run-ups of that event. The actual total energy of the tsunami is then a sum over all run-up regions of the total energy of the waves experienced by the region. In the case of the Mt. St. Helens and Indonesian tsunami, the respective energy densities of the wave with the maximum height are 76,562,500 $Jm2$ and 3,173,742 $Jm2$, indicating the difference in wave heights. Even if this density occurs when the celerity is small, approximately 1 m/s, then the actual power per meter wave front, according to the above formulae, of each wave is 76.6 megawatts and 3.2 megawatts, respectively.

The total energy per meter wave front, considering all run-ups, of each tsunami is 138,578,000 *J/m* for the St. Helens event and 14,846,600,000 *J/m* for the Indonesian event. These values are much more indicative of the contrast in total destruction caused by each tsunami than the previous measures of magnitude or intensity by maximum event wave height alone. If, again, a conservative estimate of celerity at 1 *m/s* is used, the actual power per meter wavefront of each wave is 138.6 megawatts at Mt. St. Helens and 14.8 gigawatts in the entire Indonesian tsunami, respectively.

In all, that's 14,800 gigawatts per km of shoreline for the Indonesian tsunami and 138.6 gigawatts per km of shoreline at Spirit Lake. Spirit Lake, prior to 1980, had a surface area of about 5.26 square kilometers, which represents approximately 8 km of shoreline. That means 1100 gigawatts of power were delivered by the Mt. St. Helens tsunami to the shores of Spirit Lake. The total length of shoreline affected in the Indonesian tsunami is vast because its effects were felt around the world. It has been estimated (McIntyre, 2005) that Sri Lanka alone was hit by a total power of half a terawatt (0.5×1012) by the Indonesian tsunami.

APPENDIX IV. Derivation of the LP-Index

We describe how the association of the LP-Index with the power of a tsunami event is eventually derived. Recall the power of a tsunami event is defined as:

$$P_{tsunamievent} = {}_{allwaves} P_{wavefront} * D_{shoreline}$$

First, remove shoreline distance from the variable list (the run-up factor remains). Notice, per region, an average $D_{shoreline}$ could also be used to compute $P_{tsunamievent}$ (another constant). This provides an association of event power with event power per meter shoreline:

$$P_{tsunamievent} \quad P_{tsunamievent\ per\ meter\ shoreline}$$

Next, approximate tsunami power using the upper bound of power per meter wave front for the highest wave in the event. The maximum wave height observed in a tsunami event determines the maximum power per meter wave front of the event:

$$P_{wavefront} \quad P_{wavefront\ of\ high\ wave}$$

In this way with N = number of run-ups, we have removed the need for the sum and we have the association:

$$P_{tsunamievent\ p.ms.} \quad N * P_{wavefront\ of\ highest\ wave}$$

Because the maximum wave height, H, observed in a tsunami event determines the maximum power per meter wavefront of the event, we can further make the correspondences:

$$P_{wavefront\ of\ highest\ wave} \quad H$$

And finally

$$P_{tsunamievent} \quad N * H \ .$$

APPENDIX V. 'Top Ten' Tables

Table (i). BY DEATHS

Year	Country	Region	Wave height (m)	Run-Ups	Deaths
2004	INDONESIA	OFF W. COAST OF SUMATRA	50.9	1058	226898
2011	JAPAN	HONSHU	38.9	5776	15854
1976	PHILIPPINES	MORO GULF	8.5	30	4376
1945	PAKISTAN	MAKRAN CST	15.24	7	4000
1952	RUSSIA	KAMCHATKA	18	290	4000
1933	JAPAN	SANRIKU	29	295	3022
1998	PAPUA NEW GUINEA	PAPUA NEW GUINEA	15.03	67	2205
1923	JAPAN	SAGAMI BAY	13	103	2144
1946	DOMINICAN REPUBLIC	NE COAST	5	8	1790
1946	JAPAN	S HONSHU	6.6	298	1362

Table (ii). BY WAVEHEIGHT SHOWING DEATHS

Year	Source Location	Wave height (m)	Deaths
1958	Lituya Bay, Alaska	525	5
1980	Spirit Lake, WA	250	NO REPORT
1936	Lituya Bay, Alaska	149.35	NO REPORT
1936	Norway	74	73
1964	Alaska	67.1	124
1993	Niigata, Honshu, Japan	54	208
2004	Indonesia	50.9	226898
2000	Paatuut, Greenland	50	NO REPORT
1905	Nessoden, Norway	40.5	61
2011	Honshu, Japan	38.9	15854

Table (iii). BY DAMAGES

Note: Damages reported by the NGDC represent the dollar value at the time of the event. For the purpose of comparison, damages reported in the event years were converted to damages representing the same buying power as in 2011 using the Consumer Price Index Inflation Calculator available at the Bureau of Labor Stats of US Department of Labor.

Year	Country	Region	Wave height(m)	Run-Ups	2011-ADJ. Damages(Mil)
2011	JAPAN	HONSHU	38.9	5776	$210000
2010	CHILE	S. COAST	29	597	$30946
2004	INDONESIA	W. COAST SUMATRA	50.9	1058	$11908
1993	JAPAN	SEA OF JAP.	54	176	$1879
1983	JAPAN	NOSHIRO, JAP	14.93	227	$1807
1964	USA	PRINCE WM SOUND, AK	67.1	394	$864
1964	JAPAN	NW. HONSHU	5.8	165	$581
1960	CHILE	CENTRAL CHILE	25	1049	$570
1976	PHILIPPINES	MORO GULF	8.5	30	$530
1946	USA	UNIMAK ISL, AK	35.05	511	$302.9

Table (iv). BY WAVE HEIGHT SHOWING DAMAGES

Year	Source Location	Wave height (m)	2011-Adjusted Damages in Millions
1958	Lituya Bay, Alaska	525	$0.8
1980	Spirit Lake, WA	250	NO REPORT
1936	Lituya Bay, Alaska	149.35	NO REPORT
1936	Norway	74	NO REPORT
1964	Alaska	67.1	$864
1993	Niigata, Honshu, Japan	54	$1879
2004	Indonesia	50.9	$11908
2000	Paatuut, Greenland	50	NO REPORT
1905	Nessoden, Norway	40.5	NO REPORT
2011	Honshu, Japan	38.9	$210000

Table (v). BY RUN-UPS SHOWING DEATHS

Year Of Tsunami	Source Location	Wave height (meters)	Run-Ups	Deaths
1960	Chile	25	1049	1203
2004	Indonesia	50.9	1058	226898
2010	Chile	29	597	156
2009	Samoa	22.35	579	192
1946	Unimak Island, Alaska	35.05	511	164
2011	Iwate, Honshu, Japan	38.9	5776	15854
1964	Prince William Sound, Alaska	67.1	394	124
1957	Adreanof Islands, Alaska	22.8	323	NO REPORT
1968	Honshu, Japan	6	306	NO REPORT
1946	South Coast, Honshu, Japan	6.6	2981362	

Table (vi). BY RUN-UPS SHOWING DAMAGES

Year Of Tsunami	Source Location	Wave height (meters)	Run-Ups	2011-AdjustedDamages in Millions
1960	Chile	25	1049	$570
2004	Indonesia	50.9	1058	$11908
2010	Chile	29	597	$30946
2009	Samoa	22.35	579	$288
1946	Unimak Island, Alaska	35.05	511	$303
2011	Iwate, Honshu, Japan	38.9	5776	$210000
1964	Prince William Sound, Alaska	67.1	394	$864
1957	Adreanof Islands, Alaska	22.8	323	$40
1968	Honshu, Japan	6	306	NO REPORT
1946	South Coast, Honshu, Japan	6.6	2981362	NO REPORT

Table (vii). BY LOG POWER INDEX SHOWING WAVEHEIGHT, RUN-UPS, DEATHS AND DAMAGES

YEAR	COUNTRY	REGION	WAVE HEIGHT	RUN-UPS	Log-Power Index	Damages Adjusted to 2011 (Millions)	Deaths
2011	JAPAN	HONSHU ISLAND	38.9	5776	5.351577	$210000	15854
2004	INDONESIA	OFF W. COAST OF SUMATRA	50.9	1058	4.731203	$11908	226898
1964	USA	PRINCE WILLIAM SOUND, AK	67.1	394	4.422219	$864	124
1960	CHILE	CENTRAL CHILE	25	1049	4.418715	$570	1203
1946	USA	UNIMAK ISLAND, AK	35.05	511	4.253109	$303	464
2010	CHILE	OFF SOUTHERN COAST	29	597	4.238372	$30946	156
2009	SAMOA	SAMOA ISLANDS	22.35	579	4.111956	$288	192
1993	JAPAN	SEA OF JAPAN	54	176	3.977906	$1879	208
1933	JAPAN	SANRIKU	29	295	3.93222	NO REPORT	3022
1958	USA	SE. ALASKA, AK	525	15	3.896251	$0.8	5

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