Team Number: 225

Question: B

Year: 2009

Tsunami

Wipe out!

Mathematical Modeling Competition

Team No. 2225

Contents

Summary Paper: Modeling the devastation of a Tsunami

How physical phenomena behave and interact with society remains to be one of the greatest enigmas of the contemporary world. In fact, following the tsunami of 2004 that reminded the world that it is nature in charge of man and not man in charge of nature, various mathematical models to predict the motion and devastating effect of tidal waves have been established and proposed, such as the prediction and warning systems installed in Southeast Asia now.

This investigation analyzed the mathematical background of shallow-water waves and established a link between the yield energy of earthquakes caused by converging tectonic plates under the assumption that this energy would be transferred exclusively into the kinetic energy of the wave produced. Additionally, each impulse of the wave was taken to be an individual body of water that struck at one instance in time. Effectively, however, it was found that a mathematical model of the establishment of tidal waves would only be able to reveal a definite relationship with the devastation caused by the impact of the wave by adapting a broad and commonly ill-defined assemblage of variables. Consequentially, the investigation regarded this as a theoretical basis. Historical data was subsequently assembled and a general trend established between a broad varieties of factors that are indicative of the scope of destruction.

These factors include population density, the area of the city. We found the independent and dependent variables from major historical tsunamis and plotted them to find a relationship between them. Using the model we generated from the past events, we tried to predict what a strong tsunami would cause in major US cities given. We found that San Francisco would have the highest number of fatalities, while Lima would have the highest number of houses destroyed. The high death toll in San Francisco suggests that it would be the most significantly affected if a high-magnitude were to hit.

B. Outline of the cities investigated

The following will provide an overview of the socio/economic significance of the cities to be analyzed in the following investigation. The cities to be investigated are:

- New York (New York)
- San Francisco (California)
- New Orleans (Louisiana)
- Charleston (South Carolina)
- Hilo (Hawaii)
- Boston (Massachusetts)

+

- Lima (Peru)

Factual information has been gathered on each of the following cities. This will be implemented in later processing of the data.

New York:

Height above Sea Level (average)	0 m
Population	8,274,527 (2007)
Population density (people/km^{-2})	10,606 people/km^{-2}
State coastline	204 km
GDP (per capita)	52,800 $
City Coastline	40km
City Area (km^{-2})	1214.4

San Francisco:

Height above Sea Level (average)	15 m
Population	808,976 (2008)
Population density (people/km^{-2})	17,323 people/km^{-2}
State coastline	1344 km
GDP (per capita)	62,300 $
City Coastline	23 km
City Area (km^{-2})	600.7

New Orleans:

Height above Sea Level (average)	-3 m (below sea level)
Population	311,853 (2008)
Population density (people/km^{-2})	973 people/km^{-2}
State coastline	635 km
GDP (per capita)	38,800 $
City Coastline	40 km
City Area (km^{-2})	907

Charleston:

Height above Sea Level (average)	2 m
Population	126,567 (2007)
Population density (people/km^{-2})	385 people/km^{-2}
State coastline	300 km
GDP (per capita)	29,600 $
City Area (km^{-2})	376.5

Hilo:

Height above Sea Level (average)	18 m
Population	40,000
Population density (people/km^{-2})	290 people/km^{-2}
State coastline	1200 km
GDP (per capita)	38,100 $
City Area (km^{-2})	141

Boston:

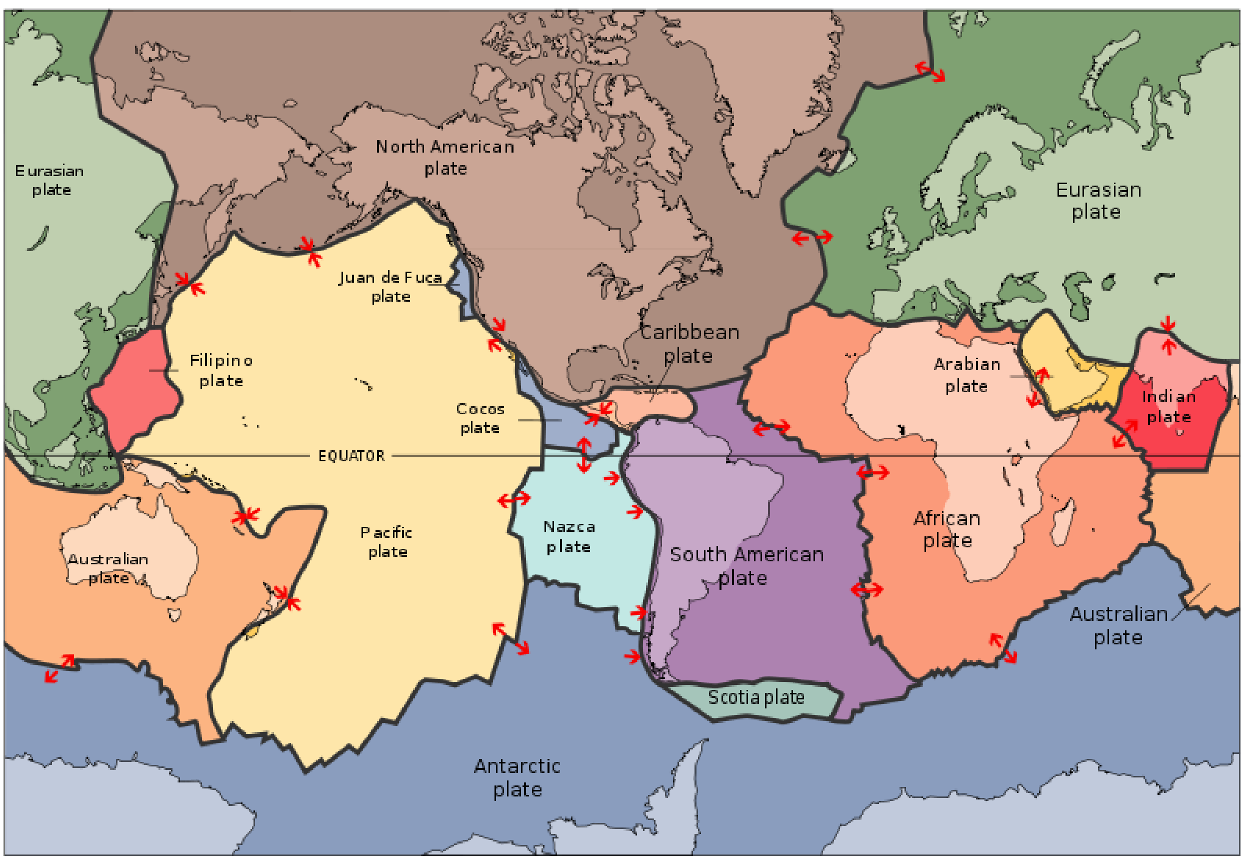
Height above Sea Level (average)	43 m
Population	609,023
Population density (people/km^{-2})	4,860 people/km^{-2}
State coastline	310 km
GDP (per capita)	58,000 $
City Area (km^{-2})	232.14

The city of choice was Lima, Peru. The reason for choosing this city was that it has been exposed to significant tsunamis in its history and thus provides a useful comparison for the other cities in the United States of America.

Lima:

Height above Sea Level (average)	43 m
Population	7,605,742
Population density (people/km^{-2})	2,846.1 people/km^{-2}
GDP (per capita)	7,600 $
City Coastline	40 km
City Area (km^{-2})	2672

C. Main epicenters near the cities



This map shows the tectonic plates that causes earthquakes, often underwater. These underwater earthquakes are the ones that cause tsunamis, so the locations where two plates meet, are likely to be epicenters of potential tsunamis. Because the nearest edge to the east coast of the US is relatively far off, it seems that tsunamis would have to travel quite far. In any case, the tectonic plates in the Atlantic are divergent, so they are unlikely to cause tsunamis. However, the ones in the Pacific are known to be convergent, meaning that one subducts the other, causing tsunamis. This is one consideration when looking at different cities. Off the west coast of South America, for example, two plates meet, making it a fairly high-risk zone compared to the east coast of the US.

D. Cause for earthquakes and tsunamis

The nature of tsunamis will be examined.

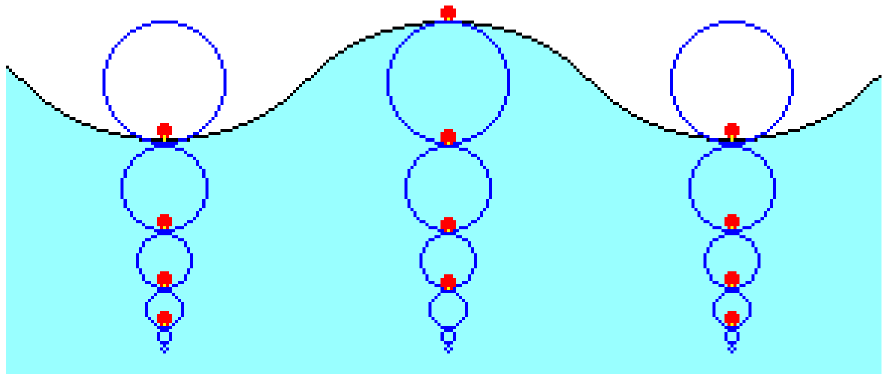
Maximum values for tsunamis are approximately:

Wave speed (open ocean)	200 ms^{-1}
Wave length	100 km
wave period	3600 s
Run-up height	30 m
Distance of inland flooding	hundreds of meters

(Data)[1]

Notably, water waves can be summarized as deep-water, intermediate and shallow-water waves. Particularly important is that water molecules move in an elliptical cycle when the wave passes. At a certain depth the particles will no longer move when the waves pass. This makes the waves of a tsunami both longitudinal and transverse.

[1] "Ocean Sciences|Research activities|Tsunamis and tsunami research." *Ocean Sciences*. Web. 16 Nov. 2009. <http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/tsunami/tsunamiphysics_e.htm#earth>.



(Picture)[2]

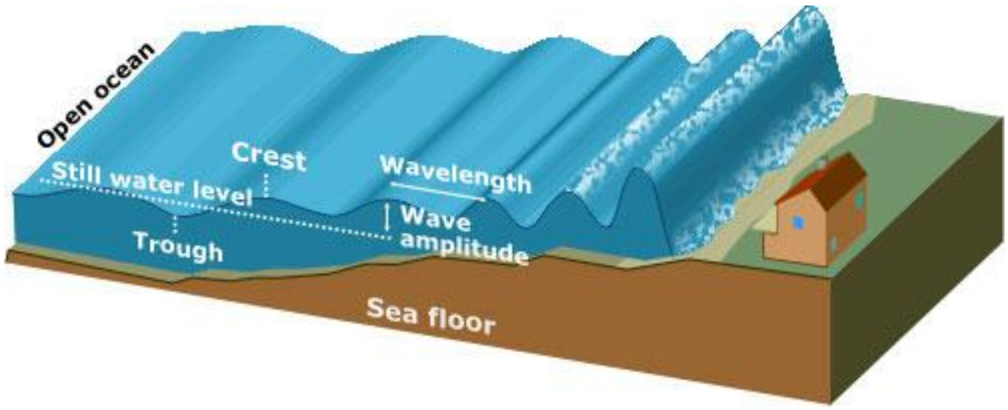
Tsunami waves may be modeled with deep-water wave properties (The wavelength is at least half the wavelength depth, i.e. the depth of impact of the wave on a body of water is half the wavelength). This means that the speed of the waves is solely dependent on the wavelength of the wave as gravitational acceleration remains constant.

$$v = \sqrt{\frac{g\lambda}{2\pi}}$$

As approaching land, tsunami waves transform to shallow water waves, i.e. While at sea the wavelength of tsunamis is extremely large, as it can thus transfer large amounts of energy over large distances, the wavelength of the wave shortens significantly as in the diagram below. The tsunami wave slows down and the kinetic energy transforms to potential energy and the amplitude of the wave builds up.

$$v = \sqrt{g\bar{d}}$$

[2] "The Physics of Tsunamis: The Harbour Wave." *UBC PhysAstro*. Web. 16 Nov. 2009. <http://www.physics.ubc.ca/~outreach/phys420/p420_05/anthony/The%20Physics%20of%20Tsunamis.htm>.



(Picture)[3]

In terms of plate tectonics, if one late subducts under another than the energy released will not only cause an earthquake but transfer most energy to the water which will form a

$$v = \sqrt{g\bar{d}}$$

$$E_K = \frac{1}{2}mv^2$$

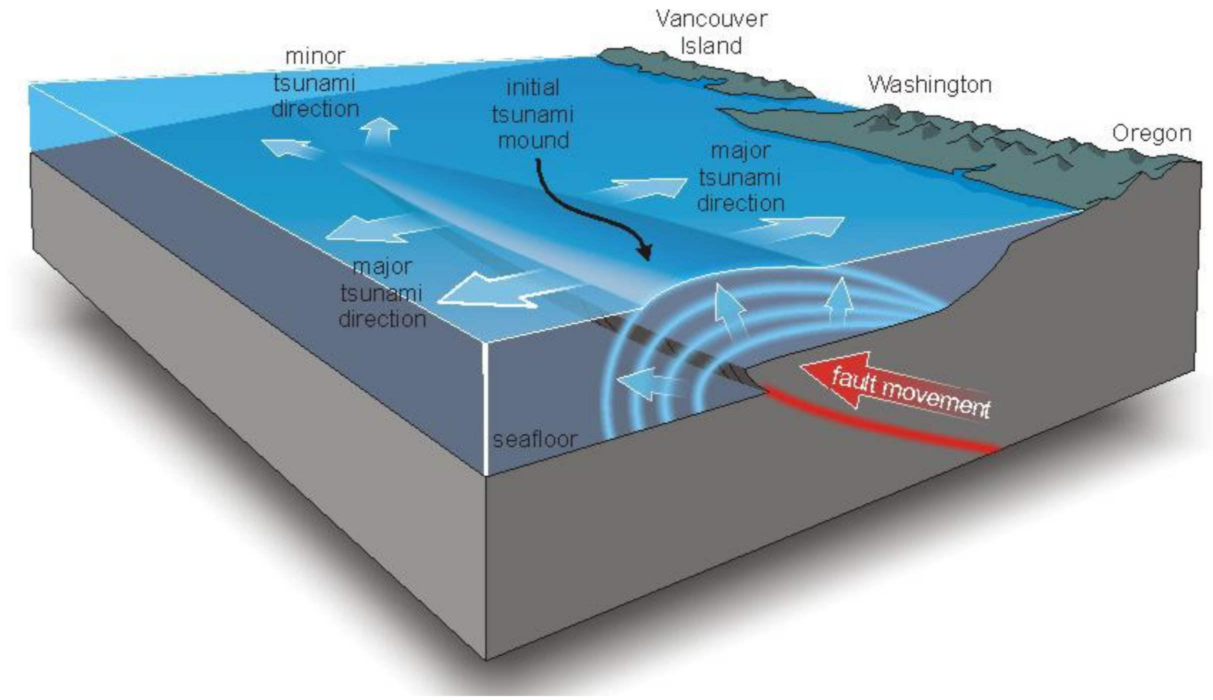
$$m = V\rho \qquad V = hlv \qquad m = hlv\rho$$

$$E_K = \frac{1}{2}hlv\rho v^2 = \frac{hl\rho v^3}{2} = \frac{hl\rho\left(g\bar{d}\right)^{\frac{3}{2}}}{2}$$

$$E_K = \frac{g^{\frac{3}{2}}\rho}{2}hl\bar{d}^{\frac{3}{2}} \qquad E_K \propto hl\bar{d}^{\left(\frac{3}{2}\right)}$$

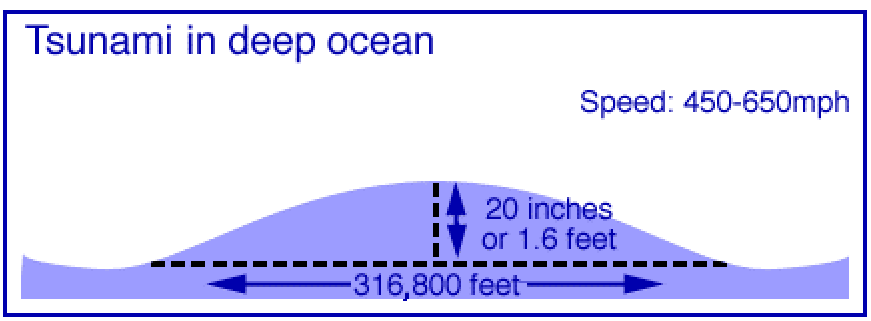
Therefore, the energy of the wave depends on the height of the wave, the length of the coastline, and the velocity of the wave. The density of water is a constant. This would mean that a city with a longer coastline would suffer more from the effects of a tsunami.

[3] "The Physics of Tsunamis." *David Newman*. Web. 16 Nov. 2009. <http://ffden-2.phys.uaf.edu/212_spring2005.web.dir/Justin_Priest/Tsunami%20Physics.htm>.

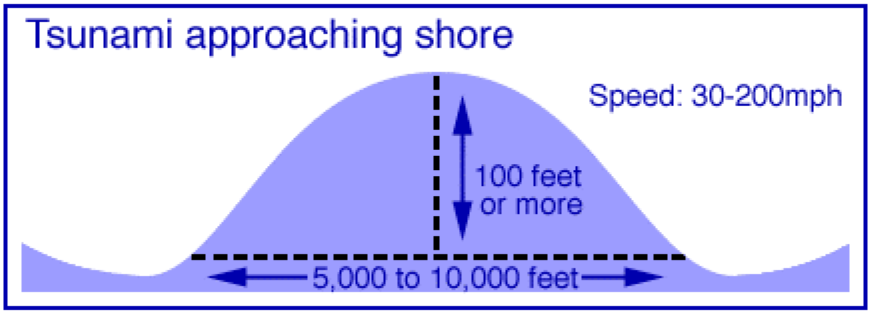


(Picture)[4]

This diagram shows the convergent collision between the plates which would cause a tsunami. In this situation, one place subducts the other, creating a powerful wave.



[4] Photograph. *Richmond California*. Web. 16 Nov. 2009. <http://www.richmond.ca/__shared/assets/Tsunami_-_Fig12408.jpg>.



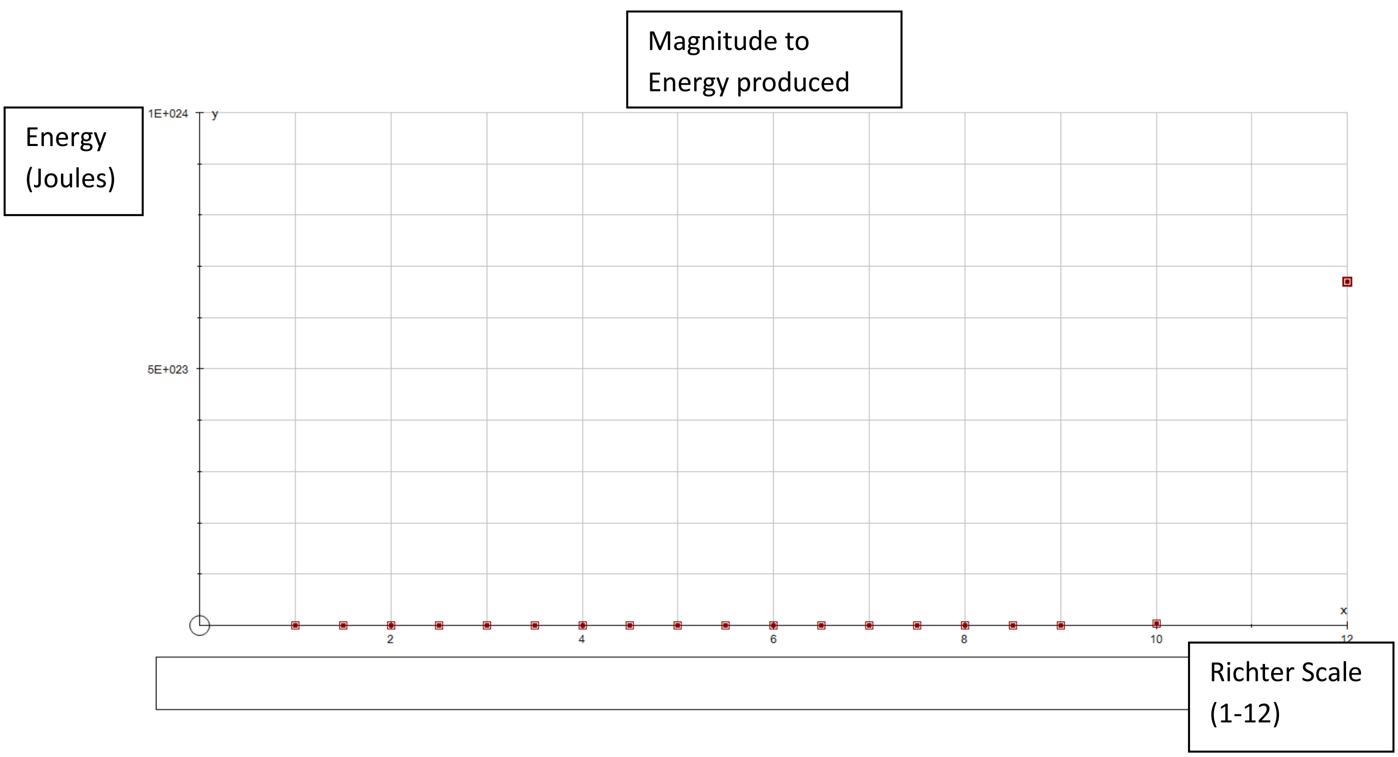
Earthquake Magnitude to Wave Energy Produced:[5]

Richter Magnitude	TNT for Seismic Energy Yield	Example (approximate)
-1.5	6 ounces	Breaking a rock on a lab table
1.0	30 pounds	Large Blast at a Construction Site
1.5	320 pounds	
2.0	1 ton	Large Quarry or Mine Blast
2.5	4.6 tons	
3.0	29 tons	
3.5	73 tons	
4.0	1,000 tons	Small Nuclear Weapon
4.5	5,100 tons	Average Tornado (total energy)
5.0	32,000 tons	
5.5	80,000 tons	Little Skull Mtn., NV Quake, 1992
6.0	1 million tons	Double Spring Flat, NV Quake, 1994
6.5	5 million tons	Northridge, CA Quake, 1994
7.0	32 million tons	Hyogo-Ken Nanbu, Japan Quake, 1995,
7.5	160 million tons	Landers, CA Quake, 1992
8.0	1 billion tons	San Francisco, CA Quake, 1906
8.5	5 billion tons	Anchorage, AK Quake, 1964
9.0	32 billion tons	Chilean Quake, 1960
10.0	1 trillion tons	(San-Andreas type fault circling Earth)
12.0	160 trillion tons	(Fault Earth in half through center)

[5] "Richter Magnitude." *The Nevada Seismological Laboratory*. Web. 16 Nov. 2009. <http://www.seismo.unr.edu/ftp/pub/louie/class/100/magnitude.html>.

A **ton of TNT**, (a metric ton = 1000 kg) is therefore 4.184 x 10^{9} [6]

Magnitude	Weight of TNT (tons)	Energy per Ton of TNT (joules)	Total Energy Produced in Joules
-1.5	0.0003125	4184000000	1307500
1	0.018575	4184000000	77717800
1.5	0.2	4184000000	836800000
2	1	4184000000	4184000000
2.5	4.6	4184000000	19246400000
3	29	4184000000	1.21336E+11
3.5	73	4184000000	3.05432E+11
4	1000	4184000000	4.184E+12
4.5	5100	4184000000	2.13384E+13
5	32000	4184000000	1.33888E+14
5.5	80000	4184000000	3.3472E+14
6	1000000	4184000000	4.184E+15
6.5	5000000	4184000000	2.092E+16
7	32000000	4184000000	1.33888E+17
7.5	160000000	4184000000	6.6944E+17
8	1000000000	4184000000	4.184E+18
8.5	5000000000	4184000000	2.092E+19
9	32000000000	4184000000	1.33888E+20
10	1E+12	4184000000	4.184E+21
12	1.6E+14	4184000000	6.6944E+23



[6] "StateMaster - Encyclopedia: Megatons." *US Statistics, State Comparisons*. StateMaster. Web. 16 Nov. 2009. <http://www.statemaster.com/encyclopedia/Megatons>.

An Equation was formed using best fit line on the calculator to match the data by 99.95%. Equation for Magnitude to yield energy = $19316684.22*24.73^{x}$ and this equation must be divided by two since the wave of energy will split into 2 at the fault, sending waves into either direction.

E. Assumptions and Limitations

Assumptions:

- Depth of the ocean from epicenter is constant until beginning of sandbank is reached
- The wave does not lose energy until reaching the coastline, i.e. total energy is constant. This depends on the strength of the earthquake.
- All yield energy of the quake will be transferred to the water.
- The cause of the earthquake and thus tsunami is identical for all situations (This will be a slipping in the megathrust fault, i.e. this will be taken as the epicenter)
- The source of the tsunami will be a point along a fault line, i.e. the source is only at one point
- The tsunami will not be considered as a series of waves, but as one block of water where all waves will be combined.

Limitations:

- Square Waves used for calculations.
- Coastline assumed to be linear and parallel to the tsunami.
- Inaccuracies in the measurement of coastlines.
- Used average depth of ocean in calculation.

Realization:

Although these calculations are following the idea that the strength of impact of the tsunami will depends on the magnitude of the earth quake, however,

Instead:

Instead, we will look at the:

1. Population density to death toll of a tsunami
2. Area of the City to mass of destruction (measured by quantity of homes destroyed)

By looking at these two relationships by researching past tsunamis with similar earthquake magnitudes, it can be determined the effect on each city listed above of a strong (7 and above) tsunami.

F. Model

New Assumptions and Limitations:

Assumptions:

- Water depth is consistent in all areas
- Earthquakes occurs in the same distance away from the city in all cases
- Sand bank leading to land is the same in gradient and distance
- Abnormal waves formed by tsunamis are the same in shape, height, and volume and that the general nature of the wave is constant
- Land level above water in all cities are the same
- Population density directly affects quantity of people who die
- Area of city directly affects the quantity of homes destroyed
- The area exposed to the ocean of the city is constant

Limitations:

- Land level above water is inconsistent in city and can't be measured
- Sank banks have various gradients which can affect the nature of the tsunami wave including strength of impact
- Reflected waves and of alternative movements of the waves cannot be measured when the wave hits a possible obstacle before the bay of city and the effect on the city can be identified
- The strength of wave cannot entirely be determined directly by the magnitude of the earthquake due to previously mentioned limitations

Data Collection:

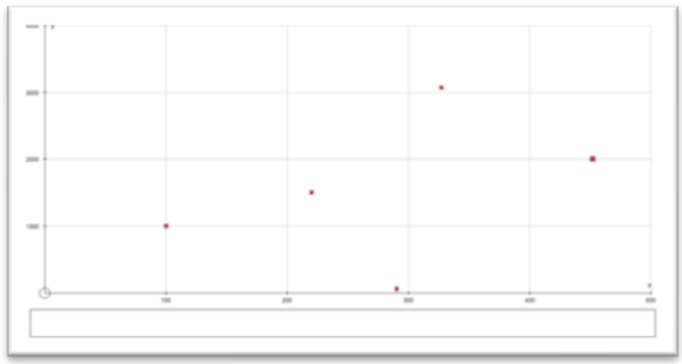
We collected data by looking at previously occurring earthquakes in Japan and 1 from Hawaii in the past 100+ years that had an initial earthquake of greater than a 7 magnitude to find a more constant trend that can be expressed later as an equation. Since both areas are islands in the Pacific Ocean, more commonalities between the scenarios can be made to hopefully made a connection between the variables in the desired equations above.

	Hilo, Hawaii	Honshu, Japan	Showa, Japan	Nankaido, Japan	Sanriku, Japan
Richter Scale	9.5	7.2	8.1	8.4	8.4
Land Area (km^2)	141	227962	1000	18800	140500

Population density (People per km²)	290	451.8	327	220	100
Casualties	61	2,000	3068	1,500	1,000
Homes destroyed	541	40,000	5000	1,451	7,000
Year of impact	1960	1896	1933	1946	1933

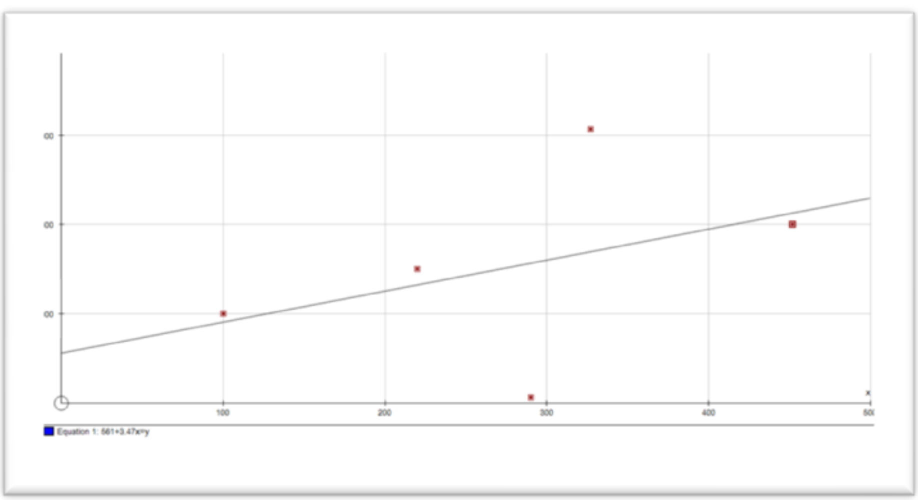
Population density to Death total Equation:

	Population density (km^2)	Casualties
Sanriku, Japan	100	1,000
Nankaido, Japan	220	1,500
Hilo, Hawaii	290	61
Showa, Japan	327	3,068
Honshu, Japan	451.8	2,000



The data shows an overall upward trend as the greater the population density, the great the casualty. The data from Hilo is an outlier in this situation that could have been caused due to possibly elevation above ocean level.

By inputting this data in my Ti-84, I can find a best fit line and check through the compatibility percentage.



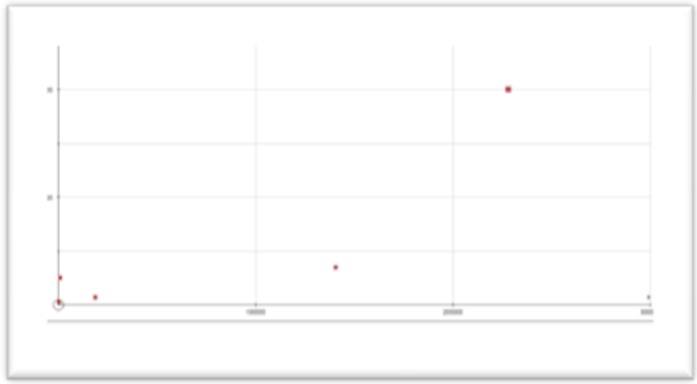
Quantity of Deaths = 561 + 3.47(Population density) Match to Data: 40%

The general trend is now most accurate described as a positive trend. This equation states as the density of the population increases by 1, the total deaths per tsunami increases by almost 3.5 people. And per tsunami 561 people automatically die. A flaw with this equation is that when there is densities of 0, people still die even though no people would be present in the area.

Now we must create an equation for the quantity of damage to homing property in relation to the area of the city.

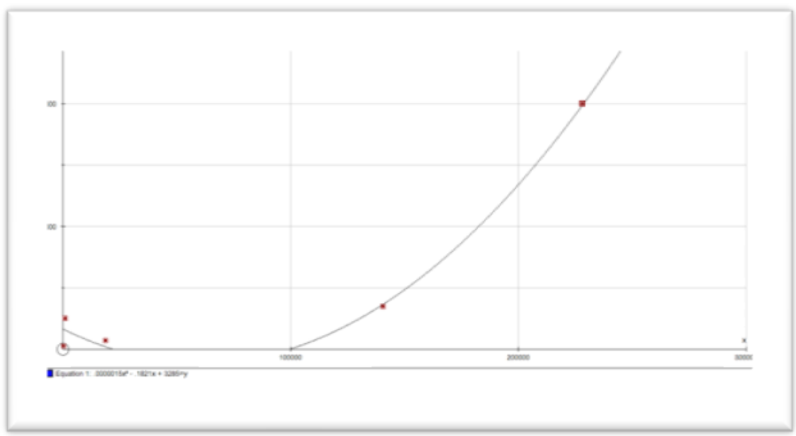
Area of city equation to quantity of homes destroyed:

	Land Area (km^2)	Homes destroyed
Hilo, Japan	141	541
Showa, Japan	1000	5000
Nankaido, Japan	18800	1,451
Sanriku, Japan	140500	7,000
Honshu, Japan	227962	40,000



Using the previous method of finding an equation to match this data, we will find the best fit line that describes the trend occurring.

Quantity of houses destroyed = .0000015x^2 - .1821x + 3285 Accuracy to data: 98.9%



This equation also describes an upward trend, as the land area increases. However, this graph dips into negative values which create an inaccuracy due to the point that houses cannot appear when tsunamis occur. So when a value is negative another assumption will be made that the total houses destroyed is 0. To solve this problem, the x value will have 100000 added to it since that is when x = 0 and all values past that do not go below 0 so an obvious trend can then be used.

So which city would suffer the most detrimental effects if a high level tsunami?

<u>Data of each City + Lima:</u>

Death Tolls:

Magnitude: 7 or above

	Population density (people/km²)	Area (km²)
Hilo	290	141
Charleston	385	376.5
New York	10,606	1214.4
Boston	4,860	232.14
New Orleans	973	907
San Francisco	17,323	600.7
Lima	2,846.10	2672

Finding Death toll:

Quantity of Deaths = 561 + 3.47(Population density)

Quantity of houses destroyed = .0000015(area+100000)² - .1821(area+100000) + 3285

	Total Fatalities
Hilo	1,567
Charleston	1897
New York	37,364
Boston	17,425
New Orleans	3,937
San Francisco	60,672
Lima	10,437

	Quantity of homes destroyed
Hilo	120.72
Charleston	148.8
New York	250.06
Boston	131.57
New Orleans	212.66
San Francisco	175.69
Lima	431.24

Death Toll Ranking:

1. San Francisco
2. New York
3. Boston
4. Lima
5. New Orleans
6. Charleston
7. Hilo

House Destruction Ranking:

1. Lima
2. New York
3. New Orleans
4. San Francisco
5. Charleston
6. Boston
7. Hilo

Interpreting the Results:

From the results above, we can see that San Francisco is the most fatally hit city if a large-scale earthquake were to cause a tsunami to hit all these cities. Hilo would be the least affected, both in terms of casualties and homes destroyed. However, in terms of house destruction ranking, Lima would be the most significantly affected, with 431 houses destroyed, followed by New York, where 250 houses would be destroyed. In this rating San Francisco wouldn't be quite as vulnerable as the two just named. This may make it seem like there is no one city that would be the most affected. However, because lives really are more important than houses, it would be sensible to say that San Francisco would be the hardest hit, because its potential death toll exceeds any other city by far. Its death toll of 60,672 is nearly twice as much as New York's 37,364. Despite Hilo having the least devastating statistics, it has to be put into perspective that it is by far the smallest city in our comparison, therefore the fatalities might be a very high percentage of its small population.

Conclusion:

Through this investigation we attempted to understand the nature of tsunamis and their effects on different cities. Although at first we attempted to generate a model representing underwater earthquakes caused by tectonic plates moving and the amount of energy they release, we later turned to historic data and generated models based on these past events. We initially heavily focused on a very mathematical model, deriving the kinetic energy of the waves depending on various factors, but realized that this exceeded our mathematical knowledge. Therefore, we changed the course of our investigation to predict the future by analyzing major past tsunamis all over the world. Although this forced us to make some assumptions and leave out some details, it enabled us to compare the different cities in the US and one of choice, Lima, effectively. We defined devastation by fatalities and destruction of homes. We found that San Francisco would have the highest number of fatalities, while Lima would have the highest number of houses destroyed. The high death toll in San Francisco suggests that it would be the most significantly affected if a high-magnitude were to hit.

A vulnerable world: Tsunami in San Francisco

Written for the *San Francisco Chronicle* (Cover story)

Recalling the 300,000 lives lost in the 2004 tsunami that struck south east Asia and devastated the coastal areas of Thailand, Indonesia, India and even Bahamas, entirely erasing all forms of livelihood on the vulnerable islands such as the Bahamas, reminds of the immense magnitude of energy that waves carry, catapulting whole cities into the chasm of absolute devastation. Although this may at first seem exaggerated and, perhaps, overstated, one must only reminisce about the destruction caused by water in New Orleans. In addition, recent findings of a mega tsunami that struck New York City two-thousand years ago as ignited international fears that the United States is at the brink of one of the greatest natural disasters in the history of civilization as we know it. The task thus is to predict the devastation that various sized earthquakes and the generated tsunamis may cause.

Do tsunamis pose an imminent threat to San Francisco? A single answer to this question can, unfortunately, not be given: 'Yes', 'no' and the good old fashioned 'maybe'. Are tsunamis a *potential* threat: certainly.

First one must understand how tsunamis are formed. In terms of plate tectonics, at a fault where plates collide one plate with a higher density will progressively subduct below the other. This will cause a tectonic uplift which will, once the frictional forces are overcome, suddenly shift large masses of water, thus releasing energy. This produces what is known as shallow-water waves. These have a large wavelength, often in the range of a few hundred meters, small amplitude and travel with tremendous speeds. Consequentially, the wave loses little energy as it may travel from the point of epicenter across the oceans to city of San Francisco. The map below outlines the general movement of the tectonic plates.

(Sciencelearn.org)[7]

Only convergent plates will pose a serious threat of tsunamis for San Francisco. Therefore, the Juan de Fuca plate near San Francisco will be an unlikely cause for a tsunami. However, the eastern fault lines of the pacific plate qualify for the necessary conditions that may stimulate a tsunami.

Undoubtedly a tsunami that would strike San Francisco would be fatal. With an approximate city shoreline of 48 kilometers, San Francisco city is exposed to the ocean openly along a

[7] "Tectonic plate boundaries | Sciencelearn Hub." *Sciencelearn Hub*. Web. 16 Nov. 2009. <http://www.sciencelearn.org.nz/contexts/earthquakes/sci_media/images/tectonic_plate_boundaries>.

waterfront of 12 kilometers.[8] Notably, it is not equipped with tidal barriers such as other US cities. Its geologic foundations are typical for California, composed primarily of sandstone and volcanic rock. Arguably this has made San Francisco prone to earthquakes and one of the most hazardous areas in the United States in the case of a natural disaster as such. Similar to when the earthquake of 1906 brought destruction to the city, a tsunami would too. This is indicated by an average elevation of 15 meters above ground level, a figure that is ambiguous as the cities highest point, Mt. Davidson, has a maximum elevation of approximately 286 meters above ground level, while most of the city itself is closer to sea level. Therefore, the city remains exposed to a possible tsunami threat but is nonetheless at an advantage due to its geologically defined elevation above sea level.

Although due to Tsunami evacuation zones, established in 2005 by the National Oceanic and Atmospheric Administration (NOAA) and a multiplicity of awareness campaigns in the California region, the likelihood of significant human costs is reduced significantly, one must consider the monetary cots that a tsunami will entail.

Based on historical data a variety of factors have been examined. These are population density in the region, total population, area flooded, average level of elevation, private property destroyed, total area of the cities influenced, GDP of the city (i.e. the economic significance) and the casualties of the defined tsunami, related to the magnitude of the quake and the yield energy (on average) emitted by the occurrence thereof – under the assumption that this energy has not been degraded but in fact transformed into kinetic energy conserved by the momentum of the resulting wave.

The results obtained then provided a historical trend that revealed the development of tsunami impacts for various sized earthquakes. Amongst other cities in the United States, San Francisco was compared to this historical trend to provide the theoretical basis for a holistic but logic interpretation of how this trend would apply to San Francisco.

The current tsunami evacuation zone is highlighted in the diagram below.

(Tsunami Evacuation Zone San Francisco)[9]

[8] *Earth Quake Grapher*. Web. 16 Nov. 2009. <http://www.sfcvb.org/media/downloads/travel_media/sf_facts.pdf>.

[9] "Geographic Systems." *ABAG: Geographic Information System*. Web. 16 Nov. 2009. <http://gis.abag.ca.gov/website/Tsunami-Maps/viewer.htm>.

However, the investigation showed that the urban organization of San Francisco is indicative of a far more fatal effect of an impacting tsunami wave. With the highest population density, San Francisco is likely to have the most fatal consequences for an earthquake above 7.0 on the Richter Scale. Notably, the epicenter of this quake could be at any one point in the pacific and San Francisco would always be affected. As the sandbank before the San Francisco is has an average length of approximately 40 kilometers, the shallow-water waves of potential tsunamis may not increase in amplitude as significantly as they may in Boston where the sandbank is 410 kilometers long. Instead, however, the inversely related velocity of the wave and thus momentum of the propelled body of water will be larger for San Francisco. Death toll may thus accelerate.

In a historical context this pattern is vindicated, but one may hope that history is not to be repeated.

However, in essence, one must never forget: this is a vulnerable world.

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