A Simulation of a Tsunami Model Using Geographical Information Systems

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Abstract

Tsunamis can sometimes be more destructive than the earthquake that caused them. Damage from a tsunami comes not only from the tsunami wave itself, but also the rapid retreat of water prior to arrival of the tsunami wave and the debris carried by the tsunami wave add to the destructive potential. In addition, fires started by the preceding earthquake are often spread by the tsunami waves. Researches are now being made in the studies for its behavior. This project worked on creating a Geographical Information System that could represent a tsunami model with regards to the calculating the extent of damage and other specifications to aid in the study of tsunamis. In particular, it implements wave modelling and other related models to simulate a tsunami on the area of Talin Bay.

Keywords: Tsunami model, Geographical Information Systems (GIS), Tsunami, Earthquake, Modeling, Simulation

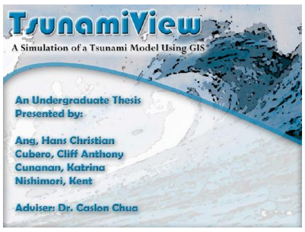
1 Introduction

GIS can be a useful tool in handling surveys and analyzing a data set for a specific problem like tsunamis. A tsunami is a series of ocean waves generated by any rapid large-scale disturbance of the sea water. Most tsunamis are generated by earthquakes, but they may also be caused by volcanic eruptions, landslides, undersea slumps or meteor impacts. In the deep ocean, a tsunami is barely noticeable and only cause a small and slow rising and falling of the sea surface as it passes. Only as it approaches land does a tsunami become a hazard. As the tsunami approaches land and shallow water, the waves slow down and become compressed, causing them to grow in height. In the best of cases, the tsunami comes onshore like a quickly rising tide and causes a gentle flooding of low-lying coastal areas.

The project focused on modelling a tsunami using GIS on a specific coastal area. The coastal area is represented as a map, where the map consists of blocks, and each block represents a data of the whole area. The system works in a way that the user selects the area, represented by blocks, to be affected by the earthquake including its specifications like Richter scale, etc. After entering inputs, the GIS, using formulae and equations, would give the result and say whether a tsunami will occur or not when an earthquake occurs in that specific coast line. If a tsunami will occur then the system would show the damage caused by the tsunami.

2 The Tsunami View System

The system (see Figure 1) is capable of calculating and simulating three processes of tsunami evolution namely, generation by an earthquake, propagation, and inundation over dry land given the bathymetric map and the inputs from the user (epicenter and magnitude of the earthquake). Aside from these three stages, it is also capable of computing for the damage brought about by the tsunami. It employs the linear shallow water wave equations.



TsunamiView
A Simulation of a Tsunami Model Using GIS

An Undergraduate Thesis
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Figure 1: Start-up screen of TsunamiView.

The system works on a predefined map with predefined infrastructures. Each infrastructure has its own attribute such as the height, what kind of infrastructure it is, the cost of the infrastructure and the latitude and longitude where it is located.

The occurrence of a tsunami will not be always possible because a tsunami occurrence depends on the inputs of the user. If the input values cohere with the tsunami generating inputs, then there will be a tsunami in the simulation otherwise, the simulation shows the behavior of the wave depending on the inputs.

Outputs of damage analysis are still displayed even if there is no tsunami occurrence. If there is no tsunami, then the damage analysis only shows of default values of the damage percentage. The simulation starts with a one hundred percent value indicating that the infrastructure is not yet damaged. This serves as the default value if no tsunami has occurred.

The functionality to create the map to be used for the simulation is not part of the system. The map is pre-defined using ArcView 3.2. The system only accepts earthquake magnitude values from 1.00 to 10.00 representing the values in the Richter scale.

The longitude and latitude for the epicenter particularly is limited within the map. The test case map used in the system is the Talim Bay. A map image of Talim Bay is shown in Figure 2.

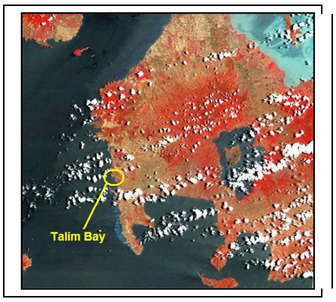

Figure 2: Land satellite image of Western Batangas[1]

The user is not allowed to edit the map. The user is only allowed to pinpoint the epicenter of the earthquake through mouse click or specify the latitude and longitude of the epicenter.

The epicenter should only be in bodies of water. The historical data about the past earthquakes guides the user on where to place the epicenter.

The system only takes one epicenter as the source of the earthquake. Records of earthquakes show that for a certain earthquake, there is only one epicenter.

Aftershocks are not considered and are only useful in determining the size of the fault that moved. There are already existing equations in order to determine the length and width of the fault that moved.

3 Architectural Design

Fundamentally, the functions of Tsunami View can be summed into three main functions: computation, simulation, and summary. In all modules, map data are accessed through a map object component as illustrated in Figure 3. Map is utilized in mostly all modules since it is here where all computations are dependent. The map is where the bathymetry and other geographical data are taken from in order to compute the generation, propagation, and inundation of tsunami waves.

The computation module handles all computations regarding the wave propagation from a given epicenter. The simulation module handles the graphical representation of the logs obtained from the computation module. The summary module is available to the user once the computation ends. The summary module is basically for damage analysis.

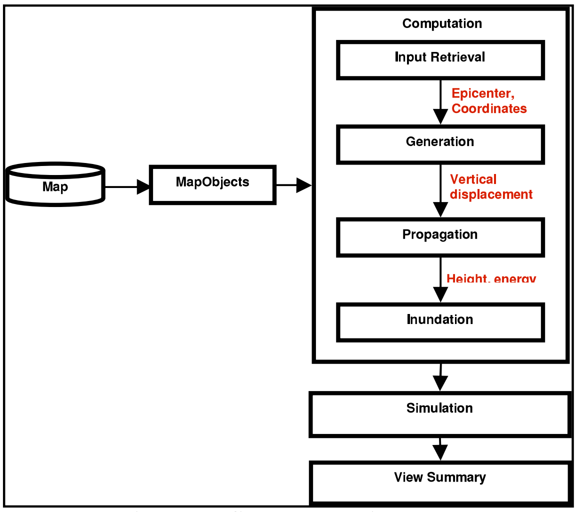

Figure 3: System architecture

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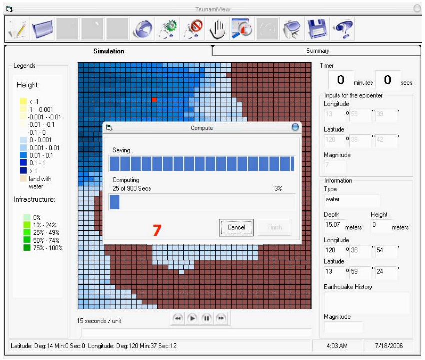
[1] Image source from Dr. Licuanan obtained from Bro. Alfred Shields, FSC Marine Station in Lian, Batangas

3.1 Computation Module

The computation module would include functions from the pinpointing of epicenter, to the tsunami generation, tsunami propagation, and tsunami inundation. Basically, the computation module comprises more than half of the whole system's functionalities. The epicenter would be pinpointed using a mouse by the user and the longitude and latitude would be generated as inputs for the simulation. There is also a marker in the map representing the sources or epicenters of past earthquakes. The user is also required to input the magnitude of the earthquake to be generated. The computation starts only after these inputs are filled.

The computation progress can be monitored through the progress bar shown in Figure 4. While the system is computing, it displays a preview of the map for every 30 seconds. The wave would be represented by the different shades of color blue. The shade of the color depends on the height of the wave.



Saving...

Computing
25 of 900 Secs 3%

Timer
0 minutes 0 secs

Inputs for the epicenter
Longitude 13 ° 59 " 39 '
Latitude 120 ° 36 " 42 '
Magnitude 7

Information
Type water
Depth 15.07 meters Height 0 meters
Longitude 120 ° 36 " 54 '
Latitude 13 ° 59 " 24 '
Earthquake History
Magnitude

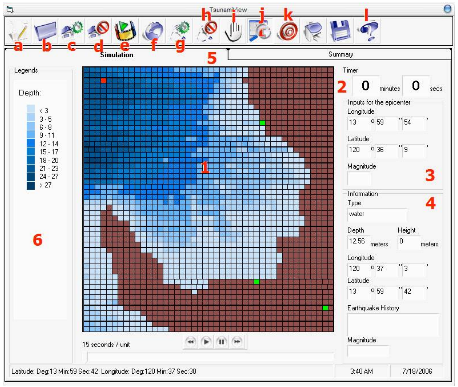
Latitude: Deg:14 Min:0 Sec:0 Longitude: Deg:120 Min:37 Sec:12 4:03 AM 7/18/2006

Figure 4: The computation module interface.

The infrastructure is initially assigned the color green. The damage inflicted by the wave in the infrastructure is represented by the infrastructure having lighter shade of green depending on the amount of damage. There is a panel in the user interface wherein it will show the respective representation of each color.

Based on Figure 5, Label 1 would refer to the map representation for the simulation process. Label 2 would indicate the timer for the whole simulation process.

Label 3 would indicate the values required before the computation can start. This would include the longitude and latitude, and the magnitude. Label 4 is where the user can see the details of the area or cell clicked by the user. This includes the longitude, latitude, depth, height and type of infrastructure. The earthquake history and magnitude in Label 4 is only enabled when the user clicks one of the historical past earthquakes represented by the color red. Label 5 is the tab that would direct the user to the simulation and view summary. Label 6 is the legends and color coding that would give the user information regarding the map representation. Label 7 is the progress bar representing the percentage of completion for the computation.



Timer
0 minutes 0 secs

Inputs for the epicenter
Longitude 13 ° 59 " 54 '
Latitude 120 ° 36 " 9 '
Magnitude

Information
Type water
Depth 12.56 meters Height 0 meters
Longitude 120 ° 37 " 3 '
Latitude 13 ° 59 " 42 '
Earthquake History
Magnitude

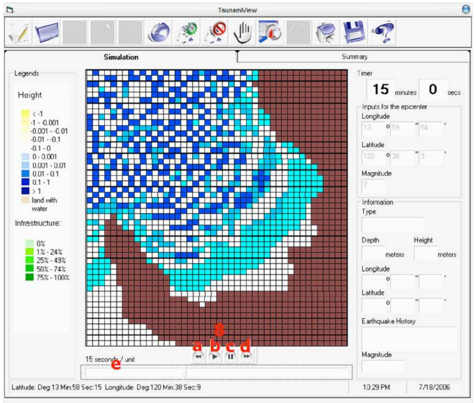
Latitude: Deg:13 Min:59 Sec:42 Longitude: Deg:120 Min:37 Sec:30 3:40 AM 7/18/2006

Figure 5: Tsunami View user interface.

3.2 Simulation Module

After computation, the user is able to view the wave computed by the computation module. The representation of the computation results are handled by this module. The whole process can be observed through the map. With controls like the slider bar, play, pause, back, and next, the user is able to scan and browse through the whole process thoroughly. Since the map is represented with colors and each color would represent a certain attribute of an object in the map, the user can observe the simulation as the color of the map changes per unit time. The user can play from a certain point and slide the slider bar any time within the whole process.

An example in Figure 6 shows the wave in the simulation represented in different shades of blue in the map. The shade of the color depends on the height of the wave. And as the tsunami propagates, the blue color of the wave would be lighter or heavier depending on the height.



Timer
15 minutes 0 secs

Inputs for the epicenter
Longitude 13 ° 59 " 54 '
Latitude 120 ° 36 " 9 '
Magnitude 7

15 seconds / unit

Latitude: Deg:13 Min:58 Sec:15 Longitude: Deg:120 Min:38 Sec:9 10:29 PM 7/18/2006

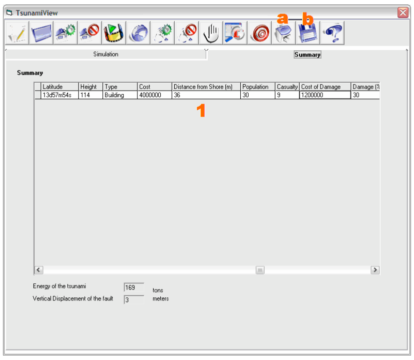
Figure 6: The simulation module user interface.

The simulation controls enables the user simulate the wave generated by the computation module. This enables users to study the whole simulation in detail. The user can review the behavior of the water based on the map representation that can be simulated. The simulation controls includes play, pause, back, next, slider bar function shown in Label 8 in Figure 6. The slider bar indicates the current time unit displayed in Label 7. The play function plays the simulation from the current slider bar position. Next and back function increases and decreases the slider bar position by 1 (equivalent to 15 seconds).

3.3 View Summary Module

In this module, the damage suffered by infrastructures, and other details concerning casualties caused by the tsunami is displayed through a table. The summary can be saved by the user as a spreadsheet file format.

This summary module contains a set of infrastructures in the map with its type, its location given the latitude and longitude of the infrastructure, the type of infrastructure, the amount of damage in percentage, the amount of damage represented by cost, distance from shore, population, casualty, and height.



Summary

	Latitude	Height	Type	Cost	Distance from Shore (m)	Population	Casualty	Cost of Damage	Damage (%
	13d57m54s	114	Building	4000000	36	30	9	1200000	30

Energy of the tsunami 169 tons
Vertical Displacement of the fault 3 meters

Figure 7: The summary module user interface.

4 Results and Observations

The equations employed in the system were validated; however it is assumed that correctness of the equations for the model had already been established.

4.1 Vertical Displacement

After the earthquake occurs, vertical displacement or elevation in the earth’s surface takes place. This is the first process in the tsunami evolution. The computation of the vertical displacement is computed by a series of equations as follows:

Obtain the moment given the magnitude of the earthquake:

$$mw = (2/3) \log mo - 16.1$$

where:
mw = moment magnitude
mo = seismic moment

Obtain the area given the magnitude of the earthquake:

$$mw = (\log A)0.98 + 4.07$$

where:
mw = moment magnitude
A = LW = area

Obtain the initial displacement given the magnitude of the earthquake:

$$\text{Moment} = \mu\ A\ D$$

where:
μ = shear modulus = 32 GPa in crust,

75 GPa in mantle
A = LW = area
D = average displacement during rupture

The equations above are patterned to the AJ Earthquake Seismometer Equation Formulas Calculator which is a seismic calculator. The computations of the system and the computations of the site yielded the same results as shown in Table 1.

Given the input:

moment = 1.258925411792 E+28 newton-centimeter or
1.258925411792 E+35 dyne-centimeter

rigidity = 30000000000 pascal or
300000000000 dyne/centimeter2

fault area = 1023700000000000 meter2 or
1.0237 E+19 centimeter2

magnitude = 8

AJ Earthquake Seismometer Equation Formulas Calculator	TsunamiView
40992.654481919 cm	4.09 m

Table 1: Results in the computation for the vertical displacement.

4.2 Wave Equation

The second process in the tsunami evolution is the propagation of the tsunami. The equation used to show how the wave behaves is the shallow water wave equation which is included in the computation module. This equation is composed of Partial Differential Equations. This means that a vertical change in a property is affected by the horizontal change of the same property and therefore coming up with a result. In the case of simulating water, a change of height (h) from previous point to the next point horizontally (x – 1, y) and (x + 1, y) together with the change of height from previous point to the next point vertically (x, y – 1) and (x, y + 1) serve as the parameters in getting the new height of the current point (x, y) as shown in Figure 8.

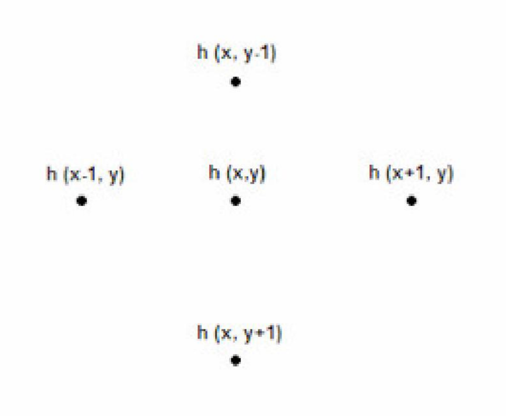


Figure 8: Visual representation of how the height is computed.

The linear equations implemented based from the partial differential equations are as follows:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-fV-g\frac{\partial h}{\partial x}-C_f\frac{U\sqrt{U^2+V^2}}{d+h}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=fU-g\frac{\partial h}{\partial y}-C_f\frac{V\sqrt{U^2+V^2}}{d+h}$$

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\{U(h+d)\}+\frac{\partial}{\partial y}\{V(h+d)\}=0$$

When the said equation was applied to the system, the result showed that changes only occurred to every other cell as seen in Figure 9. Therefore, the equation used in the program is designed to allow changes to occur to every cell.

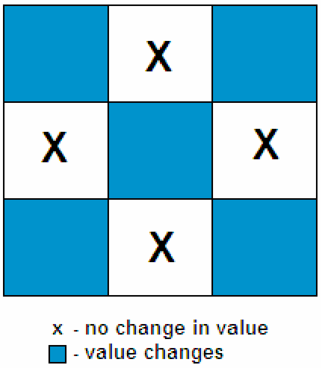


Figure 9: Application of the derived shallow water wave equation.

The first equation states that a change of U, which is the velocity of the wave horizontally, per time unit is equated to the change of height from current point to previous point horizontally over the distance between the two points and is affected by the gravitation factor.

$$u^{n}_{xy} = -g\left(\frac{h^{n-1}_{xy} - h^{n-1}_{x-1y}}{\Delta x}\right) + u^{n-1}_{xy}$$

The second equation states that a change of V, which is the velocity of the wave vertically, per time unit is equated to the change of height from current point to previous point vertically over the distance between the two points and is also affected by the gravitation factor.

$$v^{n}_{xy} = -g\left(\frac{h^{n-1}_{xy} - h^{n-1}_{xy-1}}{\Delta y}\right) + v^{n-1}_{xy}$$

The third equation states that a change of height, which is the amplitude of the wave, per time unit is equated to the sum of the changes of U and V over the distance from one point to another multiplied to the sum of the height and depth of the current point.

$$h^{n}_{xy} = H\left(\frac{u^{n}_{x+1y} - u^{n}_{xy} + v^{n}_{xy+1} - v^{n}_{xy}}{d}\right) + h^{n-1}_{xy}$$

4.3 Energy

The computations for the tsunami energy were verified by manually computing the sample data. The proponents manually computed the energy obtained from the Sumatra tsunami. The result obtained by the proponents is the same as the result stated by the paper of (Lautrup, B., 2005).

5 Conclusions

Taking into account the research and system objectives, the proponents were able to meet these objectives and were able to develop the "Tsunami View", a system that simulates tsunami using Geographical Information Systems. The algorithm used by the proponents was derived from the shallow water wave equation and was verified by Ms. dela Cruz whose MS thesis was about the derivation of the propagation equation. The algorithm was partnered with grid representation. The algorithm first computes for the momentum (u) of each cell horizontally. Then the algorithm computes for the momentum (v) of each cell vertically. Finally, the two computed values are used as parameters in computing for the height of each cell (representing the wave) at a certain time. The algorithm was able to constitute the behavior of the wave as it was simulated in the system.

The system is also able to compute for the initial displacement from the inputs of the user which is the epicenter of the earthquake and its magnitude and by using a series of equations mentioned earlier. The system is also able to simulate the tsunami graphically through rendering a certain color to a particular value according to the legends. The equation that the proponents used was used by a valid document from our resource person. The system is also able to show that the water comes into the land and is also represented by a certain color. The representation of the inundation is fully implemented. Lastly, the system is able to have a estimated computation of the damage.

6 Recommendations

The bathymetry data acquired for the creation of the map is limited. This only enabled the proponents to create a map given these data. Thus, the possible epicenter positions are limited. The current system has implemented 2,200 cells. Each cell represents 3 by 3 second which is also equivalent 100 square meters. Common models implement 2 by 2 minute which is also equivalent 4 square kilometers.

Another improvement that the proponents suggest is to implement inverse modeling. Inverse modeling is an approach to modeling a tsunami wherein a tsunami has taken place already, and research is done to mimic the said event.

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This project would not be possible without the valuable contributions from the following resource persons.

Dr. Wilfredo Licuanan
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Dr. Licuanan provided the data for constructing map of Talim Bay which was used as a test data. He also provided the basic expectations of a researcher from a prototype that simulates tsunami. He also referred the proponents to other resource persons doing work on tsunami.

Dr. Cesar Villanoy
Physical Oceanographer, University of the Philippines, Marine Science Institute
Dr. Villanoy provided explanations about tsunami and referred the proponents to other resource persons in PHIVOLCS.

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Professor, University of the Philippines – Diliman, Math Department
Ms. dela Cruz aided the proponents in understanding the shallow water wave equations, and provided the formulae from Dr. K. Satake whom she had met in her conduct of research on the math of tsunamis.

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Seismologist, Philippine Institute of Volcanology and Seismology (PHIVOLCS)
Mr. Narag introduced the proponents the concept of Wells and Coppersmith regarding the studied relationship of the area of the vertical displacement with that of the magnitude.

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