Validating Tsunami Simulations for Evaluating Tsunami Risks

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ABSTRACT

The project aims to simulate a tsunami in order to study the associated risks in the region of Monaco, in the south-east of France. To achieve this objective, an earthquake was simulated in the Ligurian Sea, strong enough to cause a tsunami that floods part of the studied area. Our model is able to shape the evolution of the resulting water level rise (waves) over time.

1 INTRODUCTION

A tsunami is a series of huge waves created by an underwater disturbance. It is created by a vertical movement of the sea floor and the consequent displacement of a body of water. From the area of origin of the tsunami, the waves move outward in all directions. Once the wave approaches the shore, it gains height. The size of the wave is also influenced by the topography of the coastline. The tsunami originates from a vertical movement of the seafloor which can be caused by e.g. an earthquake, landslides, rock falls or a volcanic eruption.

In this project, we are interested in the Mediterranean area, in particular in the Ligurian Sea, located between the coasts of southeastern France and northwestern Italy. The figure 1 shows the area designed for the purpose of the project.

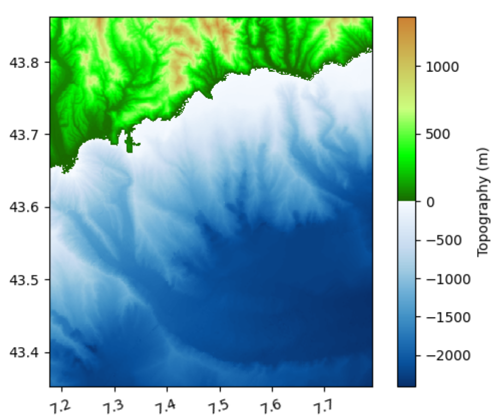

Figure 1: Area of Monaco

Although there have been no recent tsunamis strong enough to cause flooding in the Monaco area, the possibility of such an event should not be underestimated. On the one hand because of the presence of relatively close volcanic activity, and on the other hand we are in a subduction zone resulting from the sliding of the African plate under the Eurasian plate, easily attributable to strong seismic activity. According to the Euro-Mediterranean tsunami catalog, various tsunamis have been recorded, including the one of October 16, 1979, which caused the flooding of the Nice airport and waves of 3 meters.[1]

The objective of this project is therefore to study the risks associated with the propagation of a tsunami that could have adverse effects in Monaco, by simulating a real case scenario that models the effects of a tsunami at sea level.

Section 2 details the methodology used for our simulations, i.e. it is explained how an earthquake was implemented and how it underlies the tsunami. In addition, some functionality of the tool used to understand how the simulation works is explained.

Section 3 includes the results of our simulation, i.e. the effects of the tsunami in the area are shown.

Section 4 analyses the results obtained and conclusions are drawn in order to be able to respond to the problems presented by the project

Finally, section 5 elucidates the limitations of our simulation by opening a discussion on what could be improved and what would be interesting to investigate.

2 METHODOLOGY

In this session, the different approaches for implementing our simulations are shown. The various steps that allowed us to reach a sufficiently accurate model that is able to describe the behaviour of a tsunami occurring in the sea bordering Monaco are then illustrated.

2.1 Earthquake modeling

It is now explained how it is possible to simulate a tsunami earthquake with the GeoClaw tool [4] .

First, we familiarized ourselves with the GeoClaw software, which was unknown to us. For several weeks, we studied the different important parameters to be modified and their impact on the different tsunami simulations. For this purpose, we used codes provided by the developers of a simulation of the tsunami that occurred on 27 February 2010 in Chile [1]. Our aim was also to see the impact of each parameter involved in the construction of a fault (depth, width, length, etc.). The fault is the starting point of any tsunami. Once we have the precise parameters of the fault, we can predict the deformations of the seafloor. One of the main causes of tsunami are earthquakes, thus for the purpose of this project, we decided to model one by simulating the movement of the seafloor. The intensity of an earthquake can be expressed using several equations. We have used one of the best known, the Moment Magnitude, which is expressed by the following mathematical formula:

$$Mw = \frac{2}{3}\log(M0) - 10.7 \quad (1)$$

where M0 is computed as following:

$$M0 = slip * area * rigidity \quad (2)$$

So, each whole number increase in magnitude represents a tenfold increase in measured amplitude.

The deformation is caused by a slip on one or more fault planes, and can be obtained using the Okada model. This model is an analytic solution that takes in input the slip on a rectangular patch of a fault and computes the resulting deformation of the surface (for the purpose of the project we are interested in a vertical motion of the seafloor that causes a tsunami). It is important to specify that this model makes different assumptions, that are not mentioned as they are out of scope of this relation, thus the results are only an approximation of the reality. Realistic earthquake fault surfaces can be approximated by subdividing it into a specific number of rectangular sub faults each one with some properties that are covered in the table 1. Then, the Okada model is applied to each subfault.

Table 1: Subfault parameters

Parameter	Description
Location	Latitude and longitude coordinates of the centroid of the subfault
Strike	The orientation of the top edge
Dip	Angle at which the plane dips downward
Rake	Angle in the fault plane in which the slip occurs
Length	Length of the fault plane
Width	Width of the fault plane
Depth	Depth of the specified point below the sea floor
Slip	The distance the hanging block moves relative to the foot block, in the direction specified by the rake

It is important to specify that all values of these fields influence, more or less, the power of the earthquake and thus the resulting tsunami. For the purpose of the project, it is not of fundamental importance to know precisely the role of these values, however it is important to know that several tests were carried out to find consistent values to achieve the goal of inundating a part of the Monaco area.

2.2 Adaptative Mesh refinement

This chapter was introduced to explain the functioning of one of GeoClaw's most important features, the adaptative mesh refinement.

Trough all the experiments we have been usign the AMR Level, an important feature of GeoClaw, allowing us to refine the results obtained during the simulations and to focus on the most relevant information to study. Adaptive refinement refinement (AMR) is a powerful mechanism that allows the grid sizes over time during a simulation. More precisely, it allows to refine logicals rectangular patches. It is defined by using different levels. The level 1 grids cover the entire domain, then some specific area of the grid can be covered with other grids (level 2) by using a refinement factor in each direction. This process can be recursively repeated to have a higher level of AMR.

In GeoClaw is possible to specify flagged regions of the domain so that all points in the region, over some time interval , will be refined to at least a minimum level and at most some maximum level. In our simulation we applied AMR on different areas to have a better understanding and more precise data on specific areas of Monaco about the consequences concerning the high of the waves.

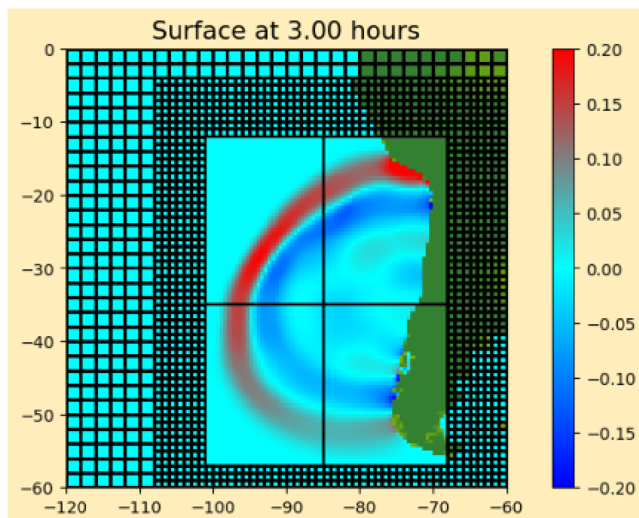

Figure 2: Example of a slip on fault and a seafloor deformation

2.3 Simulations in Monaco

In this session we are interested in the practical part, i.e. the implementation of our simulation, concerning the coastal area of Monaco.

The main objective of the project is to study the risks related to a tsunami event in Monaco. We first downloaded the topography of a large area around Monaco to get an order of magnitude of the fault to be simulated to cause a flood of the city. The data was taken from www.gebco.net [3], in the ASCII format that we felt was most appropriate for our simulations. This text file contains the topography of an area for each coordinate as accurately as possible. The topography is the altitude in relation to the sea, in our case it is given in meters. This is why we sometimes have negative altitudes, representing the depth of the sea floor.

We were then able to run tsunami simulations, just like in Chile, by modifying the tsunami parameters to see whether or not we could see a flood from Monaco. To do this, we used the gauge options provided by GeoClaw. These are points that we can set to a very precise coordinate, and observe the water level over the time of the whole simulation. More precisely, a gauge is defined by the parameters illustrated in the table 2. During the computation the value of all components of q at all gauge locations will be output to a single file fort.gauge in the output directory. Lines of this file have the form:

Table 2: Gauge parameters

Field	Description
Gauge number	Uniquely identifies the gauge
x	Latitude coordinates of the gauge
y	Longitude coordinates of the gauge
t1/t2	Time interval over which the data of the gauge should be output

This is the essential factor that allows us to know if a land area is flooded or not. In order to have the most accurate value possible, we set a very high AMR Level at the gauge locations, and a low AMR Level at the other locations to avoid having a long run time.

We then had to "zoom" our simulations on Monaco in order to have a very precise view of a potential flood. We downloaded another topography from a site that gave us more accurate data http://portal.emodnet-bathymetry.eu/ [2]. The figure 2 shows the surface height covering the area of the coastline that includes the state of Monaco, using a colour scale ranging from approximately -2500 meters (dark blue) to 1500 meters orange.

During this project, we collaborated with two groups working on different evacuation plans in case of a tsunami in Monaco. They used NetLogo, a software that takes into account the water level in a well-defined area, which studies human behavior in case of a natural disaster, and the different places where people could hide.

So they needed very precise data, which you can get from the gauges, and a very high AMR Level. The students then provided us with the geographical coordinates of a very precise area around Monaco, and using a Python script, we were able to place as many gauges as possible with a given resolution (the spacing between the gauges) over this area. We were then able to provide these results to the other groups, and change the location and strength of the tsunamis when they requested it.

To carry out the project, we needed to use a Linux interface. For that, we have done the whole project using two computers, however we will mention the characteristics of the machine with which the final simulation was carried out. Therefore, we used the Oracle VM VirtualBox software [5]. Moreover, the simulations are sometimes quite heavy in terms of storage, so we need to put a fairly large capacity of storage. The parameters of the VM are listed in the table 3:

Table 3: Hardware resources

Parameter	Value
Operating system	Ubuntu (64-bit)
Version	20.04
RAM	2048 MB
Processors	4
Storage	40 GB

These files are useful in keeping track of all surface area data for further analysis.

3 EXPERIMENTAL RESULTS

The results of our simulation can be viewed in two different ways, either by using the fort.q output files (one is created at each frame) or by taking advantage of the possibility of visualising the resulting tsunami development via the plot functionality.

Using the aforementioned files, we have the results of calculations performed on the sea height variation over time. More precisely, each file contains a specific number of information sets (one for each patch), the meaning of which is illustrated in table 6

Table 4: Header information

Field	Description
Grid number	Uniquely identifies the grid
mx	Number of lines in the matrix
my	Number of columns in the matrix
xlow	Latitude coordinate of the lower left corner of the patch
ylow	Longitude coordinate of the lower left corner of the patch
dx	Cell width in X-coordinates
dy	Cell width in Y-coordinates

3.1 Simulations in Chile

The plots representing the simulation of the tsunami in Chile in 2010 (Figure 3 and Figure 4) allow us to have a global idea of how a tsunami works, from a visual aspect.

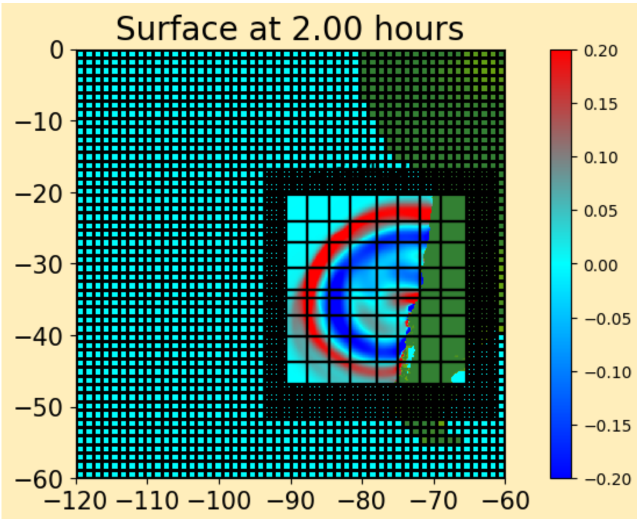

Figure 3: Tsunami in Chile at 2 hours

After two hours, the shock wave is very visible perfectly. This shows the power of the AMR. Only the interesting areas are very clear. A wave is represented by a positive water level followed by a negative water level. The second figure shows us the progress of the tsunami 3 and a half hours later. We can see that the strength of the earthquake is such that the wave is going very fast. Indeed, it has traveled 3330 km (based on the fact that one degree is approximately equal to 111 km) during this short period of time. This shows the power of the tsunami, which was equal to 8.8.

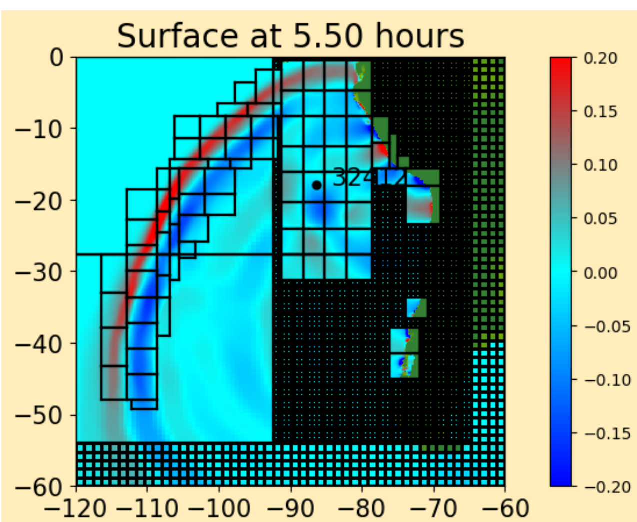

Figure 4: Tsunami in Chile at 5 hours and half

We also see that the developers of GeoClaw took a very wide window to show the extent of the tsunami impact. This was useful to know for our main purpose, thinking that a tsunami of such magnitude would be difficult to see in Monaco with the same time lag between images. We concluded that for the simulations in Monaco, we will have to put much lower time shifts to see in detail the potential flooding.

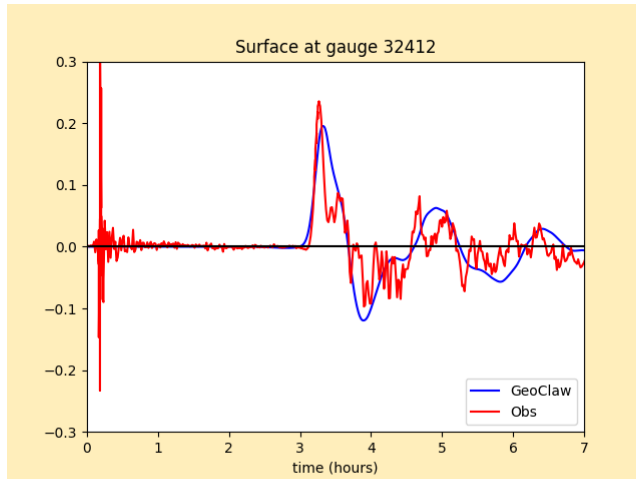

Figure 5: Level of the water in the sea

The figure 5 shows the sea level evolution over time comparing the data obtained actually recorded for the tsunami and those obtained from the simulation of the same tsunami using GeoClaw. The graph shows us that although the two trends are not the same, they both follow the same pattern

3.2 Tsunami very close to Monaco

Using the maketopo.py script, we were able to create a fault causing a flood in Monaco. In order to have consequences at the border, we first put an earthquake very close to the border. We could thus see by looking at the Figure 6a big flood at the level of the border of Monaco, but the results obtained seemed to us incoherent.

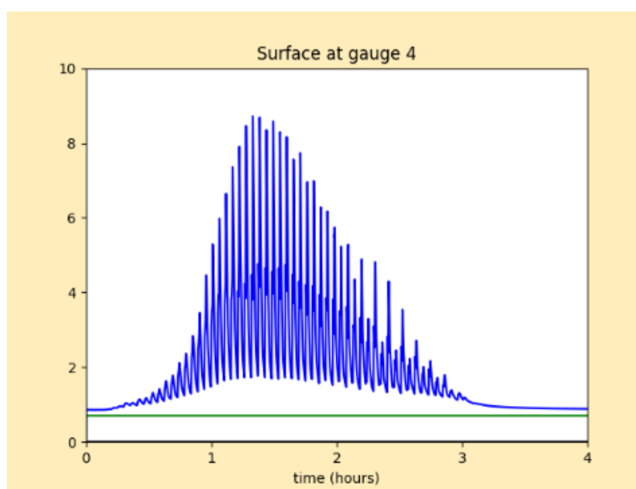

Figure 6: Flooding at the border of Monaco

Indeed, the waves rise much too high (up to 10 meters), and the oscillations seem to be much too short and fast. In order to solve this problem, we decided to put the earthquake fault further away from Monaco, in order to have more coherent results. We could add several faults together to increase the strength of the tsunami tenfold, but it seemed wise to put only one.

Here, in the table 5, are the exact data used for the fault that will be used for all the next simulations:

Table 5: Fault parameters

Parameter	Value
Location	Longitude : 7.7 Latitude : 43.4
Strike	16
Dip	16 km
Rake	15
Length	30 km
Width	30 km
Depth	20 km
Slip	15

In addition, in order to be able to give the other groups the result of our simulation, to be able to integrate it into the study of an evacuation plan for the area we created a series of files containing information about the sea elevation at each gauge location. Each file contains the following information:

Table 6: Useful information of the gauge files

Field	Description
Level	Identifies the AMR level
Time	Time of the simulation
q[1]	Water level with respect to the topography
eta	Water level with respect to the sea level

We now show the simulation results obtained using the plotting tool provided by GeoClaw. The output frames show the evolution of the sea surface height with a 15-minute break each time. Since, after X time the tsunami has no more impact and the water surface returns to normal (i.e. to the pre-earthquake situation) we have omitted part of the plots.

In the figure 7 it is shown the first frame where we can observe the situation at time t=0 when no seismic activity has yet been recorded. The sea surface level is equal to 0 (i.e. it has not undergone any change in its height). All the gauges are arranged in the state of Monaco (both in the sea and on land) and are included within the black rectangle.

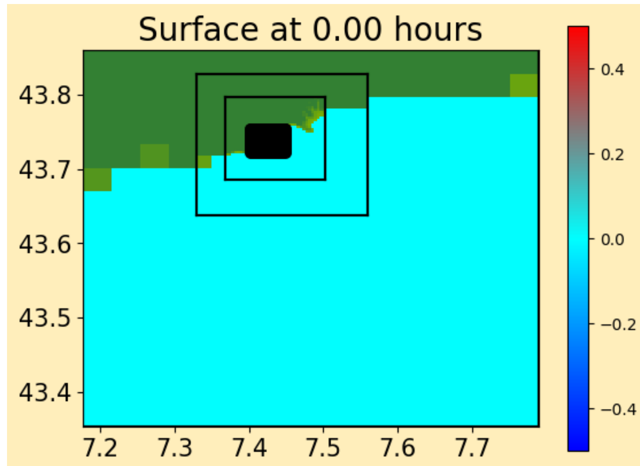

Figure 7: Frame 0

The figure 8 shows the progress of the simulation 15 minutes after the seismic event. We can see a noticeable difference from the first image, in fact in some places we observe an increase in the sea level as in the left and right extremes and a lowering of almost 0.4 metres on the north-east coast.

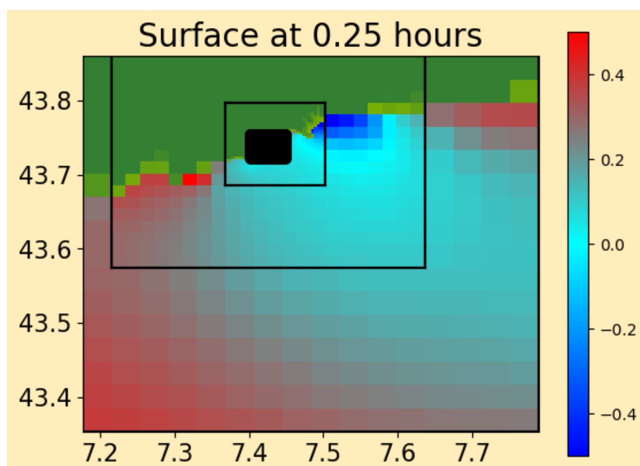

Figure 8: Frame 1

The figure 9 illustrates the state of the simulation 30 minutes after the earthquake occurred. We can see that the sea surface begins to settle at a value about 0.3 metres larger than the original value. While a thin part that touches land begins to return to its original value (in other words with a sea level elevation of 0).

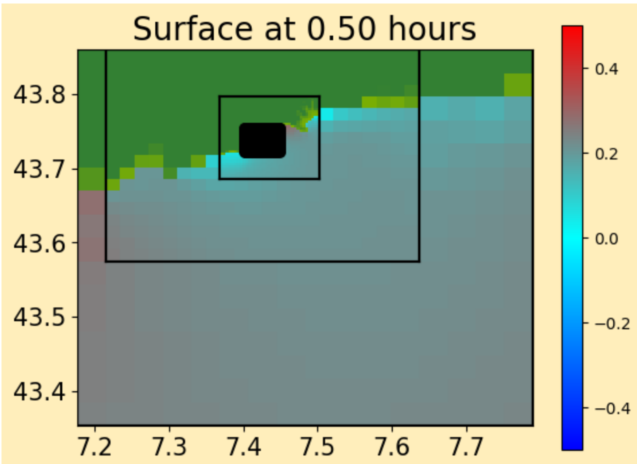

Figure 9: Frame 1

The last frame (figure 10) collects information about the rise of the sea surface after a time of 45 minutes. In this case, we observe that compared to the normal situation (before the tsunami), the sea level quasi-uniformly rose by 0.2 meters.

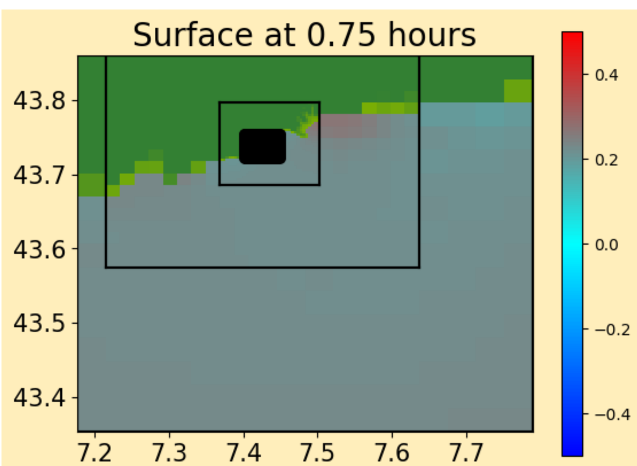

Figure 10: Frame 3

3.3 Hardware performance

In this session, we show the performance of the hardware component for the simulation of our model. The simulation comprises 5000 steps of computation and is completed after 1484.8 seconds. Note that the simulation was carried out using a single thread.

4 CONCLUSION AND DISCUSSION

4.1 Chile results

As explained earlier, in order to see the water level at a specific point over time, we use a gauge. This was placed in the sea, and we see that over time, the water level is between -0.3 and 0.3 meters, which does not seem to be that important. Since the tsunami took place, with the help of the experimental results we see that the simulations made by GeoClaw are very close to reality, and show us how reliable this software is, and how applicable it is to other places in the world.

The Chile simulation allowed us to understand the various factors that may contribute to the flooding of a particular geographic area. However, for the purpose of the project, it would not be correct to draw conclusions from this simulation. Indeed, the area of Chile and the area of Monaco are two very different areas both in size (one cannot equate a country with a state of a few kilometers). The results obtained from this simulation should therefore be interpreted as a starting point for the implementation of our simulation in the area surrounding Monaco

4.2 Monaco results

In this project, we were able to implement a quasi-realistic model of seismic activity in the Ligurian Sea, which caused a series of waves (i.e. changes in the height of the water). The deformation is illustrated by the following figures where we can see the evolution of the tsunami over time. The simulation covers a time space of 6 hours, in which, however, the tsunami is only perceptible for a duration of appreciably 2 hours. Looking closely at the results, we can see that the impact of the tsunami on the land surface relative to the Monaco area is slight and only affects a few metres from the sea.

From the results obtained, we can deduce that despite using an earthquake of magnitude 7.8,in other words a violently perceptible earthquake showed the creation of a tsunami, namely a set of waves whose height can reach about 2 meters. Therefore, the risk associated with such an event would be the flooding of the near-sea part of Monaco which could cause serious damage.

Our project, as it is to serve as the basis for the study of an evacuation plan carried out by the other groups, it produced a series of files containing information on sea level height over time for each gauge location.

5 FUTURE WORK

We demonstrated our ability to simulate a tsunami by implementing an earthquake composed of one or more faults, which allowed us to provide the other groups with the data associated with flooding in the Monaco area to study an evacuation plan. Although we achieved the objective of the project, it would have been interesting to develop a more realistic model with plausible data (a strong earthquake like ours has never occurred in the area studied). Furthermore, the hardware resources and time available only allowed us to carry out simulations with limited parameters. It would therefore have been interesting to do a simulation in which the computations are performed every minimum time delta and with the highest possible AMR level. In this case, the simulation results would be as accurate as possible.

Furthermore, it might be interesting to work with some .kml files which can be integrated into the Google Earth software in order to have a three-dimensional and thus more in-depth view of the effect of the tsunami in Monaco. Indeed, it is possible to have satellite images and see the areas impacted by the flooding through the presence of a red layer representing the elevation of the sea water level.

Another way to improve would have been to increase the resolution, i.e. the distance between the gauges we provided to the other groups. In order to have perfect results, we should have set a resolution of one meter, but the execution time would have been very long and our computer (and especially the virtual machine) would not have lasted. Moreover, we would have liked to try to work more in depth on the behavior of tsunamis and the precise effects of each parameter (length, width, depth ...), although this was not the objective of our project. In our last simulation, the impact of the fault is so strong that only half of the seafloor deformation is in the runtime window. A priori, this does not affect the results we obtained, but it would have been interesting to know if the ground deformation is really present, and especially to know how GeoClaw manages the areas where it does not know the topography. Are they considered water or land?

We would also have liked to perform tsunamis of different sizes, to determine a certain threshold where the tsunami becomes a real danger, to have an idea of where a fault would be catastrophic or not. The last track of improvement, which is unfortunately not within our competence, would be to have perfectly accurate data of the topography of Monaco. Monaco being in principle not a risk area, and a priori little studied, the site giving us the most precise site (EMODNET) does not have to date data of an exact precision of Monaco.

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A APPENDIX

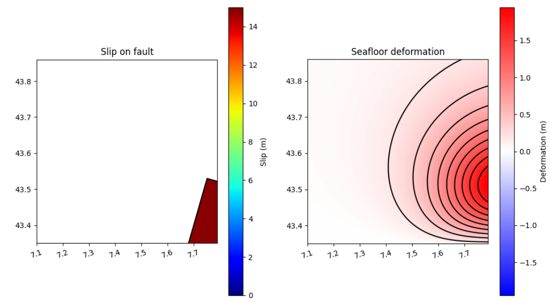

Figure 11: Slip fault and seaflor deformation 1

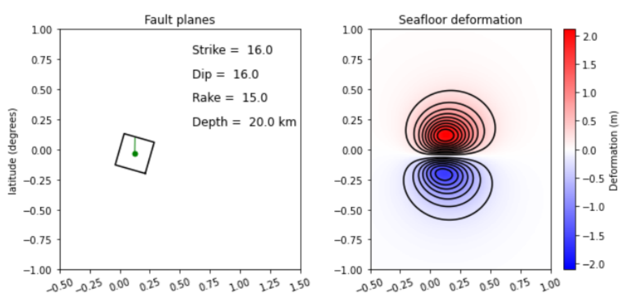

Figure 12: Fault planes and sea deformation

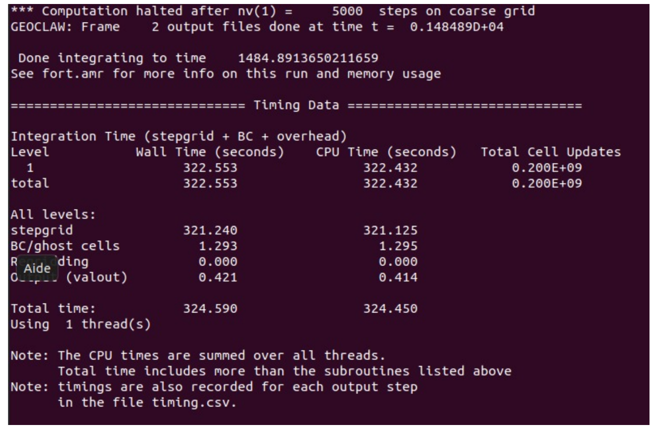

Figure 13: CPU time consumed for the simulation

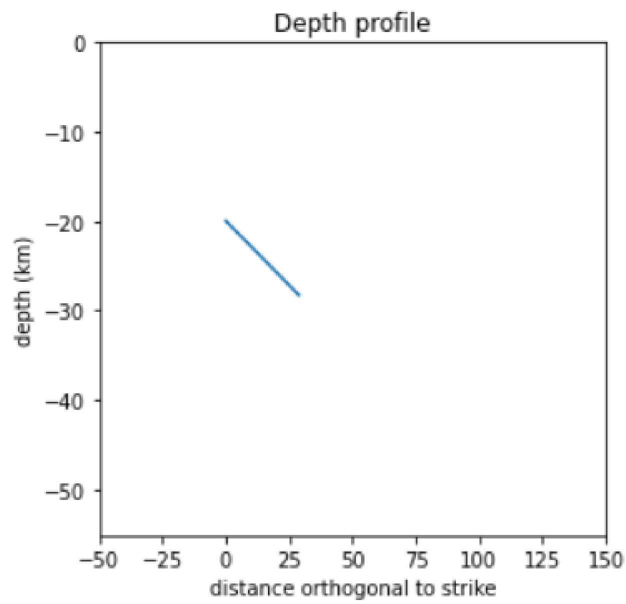

Figure 14: Depth profile