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Propagation of Tsunami Waves Multi-Factor Spread Simulation Based on CA Model

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Abstract: Tsunamis and their associated destruction have highlighted the need for real –time simulation system for accurately predicting wave spread. Such system would assist decision makers in their efforts to effectively contain potentially catastrophic event. The present work proposes a new model for spreading of waves based on two-dimensional cellular automata. This model introduces factors of propagation from diagonal and adjacent neighbor cells and includes, in a detailed form, the rate of wave spread. Further, the model is useful for both homogeneous and non-homogenous environments. Preliminary simulation results demonstrating the proposed scheme are presented. In this paper, some physically realistic ocean parameters have been considered

Keywords: Cellular automata, mathematical modeling, rate of spread, simulation, homogeneous spread

I. INTRODUCTION

Tsunamis can savagely attack coastlines, causing devastating property damage and loss of life. As a consequence, the nations in the vicinity of the Indian Ocean are now working together to establish a tsunami warning system, which should be available very soon. Till now, no technology has been found to predict a tsunami event well in advance [1]. However, a tsunami travel tone atlas for the Indian Ocean was developed recently [2][3].

Specifically, the efforts to model the growth of tsunami wave front use wave propagation techniques based on Huygens' Principle [4]. The main goal of this work is introduce a new model for predicting the spread of tsunami waves. It is based on a particular type of discrete dynamical system called two-dimensional cellular automata, 2D-CA for short. 2D – CA can be very effective at simulating complex physical systems. There are several models based on CA to model growth process in image processing, cryptography, epidemic propagation etc.[5][6][7]. The new mathematical model introduced in this paper, which is very easy to implement in software and in hardware. Moreover, the results seem to mimic the nature.

2D – CA are discrete dynamical systems formed by a finite number of identical objects, called cells, arranged uniformly in a two dimensional space. They interact locally with each other. Each cell can assume a state such that it changes in every time step according to a specific local rule whose variables are the states of some cells (its neighborhood) at previous time steps. The states considered are 0 if the cell is not traversed or partially traversed and 1 if the cell is fully traversed.

Once the tsunami is generated, its propagation is influenced by the depth of the ocean. The friction is important only in shallow water, where as in the deep ocean the effect is negligible. The dispersion effect is stronger in the direction of tsunami propagation and toward deep waters where the wave speed is the largest [8]. Both the wave amplitude and energy increase significantly toward the shoreline [9].It is known that the propagation of the tsunamis depends on the relative magnitude of the speed of the running ocean and the critical wave speed in the shallow ocean. The study of water waves relies on several common assumptions.

This means that the height cannot be higher that the initial height and reduces along the distance [10] [11].The size of the local tsunami also depends on how deep the earthquake ruptured within the earth [12][13]

Tsunamis travel outward in all directions from the generating area, with the direction of the main energy propagation generally being orthogonal to the direction of the earthquake fracture. Their speed depends on the depth of water, so that the waves undergo acceleration and deceleration in passing over an ocean bottom of varying depth [14][15]

Tsunami wave height increases rapidly in shallow water. But, as the tsunami reaches shallower coastal waters, wave height can increase rapidly [16] [17] .A trans-oceanic tsunami is one that propagates throughout the ocean in which it is generated and could cause loss of life and damage even far away from the epicenter area. For a tsunami generated by pure thrust faulting, only the primary wave fronts would be evident: one moving toward the deep ocean and one moving toward the local shoreline. In addition, there is a secondary wave front propagating to the northeast that is a continuation of the shoreward primary wave front. A slower moving tsunami is a physically higher tsunami. The waves scrunch together like the ribs of an accordion and heave upward. [18]

This paper has been developed tsunami wave simulation model using Java. It is used for finding the simulation models of the tsunami wave under two types of Tsunami, eight topological and wave conditions of Homogeneous and non-homogeneous oceans.

The rest of the paper is organized as follows: In Section 2, the basic theory of two-dimensional cellular automata is presented. In Section 3, the new model is proposed. Several tests for the new models are checked and their simulations are shown in Sections 4 and finally, the conclusions and further work are presented in Section 5

II. TWO DIMENSIONAL CELLULAR AUTOMATA

Cellular automata (CA) are discrete dynamical system formed by a set of identical objects called cells. These cells are endowed with a state, which changes at every discrete step of time according to a deterministic rule. One of the most important CA is two-dimensional finite CA. More precisely, a two- dimensional finite CA can be defined as a 4-uplet A = *(C, S, V, F)*, where C is the cellular space formed by a two- dimensional array of r x s identical objects called cells: $C = \{< i, j > , 0 \le i \le r-1, 0 \le j \le s-1\}$, such that each of them can assume a state. The state of each cell is an element of a finite or infinite state set, S; if S is finite and $|S| = k$ then S is taken to be $\mathbb{Z}_k = \{0,1,2,\dots,k-1\}$

The state of the cell < i , j > at time t is demoted by $a_{ij}^{(t)}$.

The set of indices of the 2D – CA is the ordered finite subset $V \subset \mathbb{Z} \times \mathbb{Z}, |V| = m$, such that for every cell < i , j >, its neighborhood V_{ij} is the ordered sets of m cells given by

$V_{ij} = \{< i+\alpha, j+\beta_1 >, \dots, < i+\alpha_m, j+\beta_m >$: $(\alpha_k, \beta_k) \in V$. There are some classic types of neighborhoods, but in this work only the extended Moore neighborhood will be considered; that is, the neighborhood of every cell is given by the following set of Indies:

$V_m = \{(-1,-1), (-1,0), (-1,1), (0,0), (0,1), 1,-1), (1,0), (1,1)\}$

< i-1, j -1>	< i-1, j >	< i-1, j +1>
< i , j -1>	< i, j >	< i, j +1>
< i +1, j -1>	< i+1, j >	< i+1, j +1>

Figure 1.1: Graphically the extended Moore neighborhood of a cell <i, j >

In this case, we can distinguish two types of neighbor cells of < i, j > : adjacent neighbor cells,

{< i-1, j >, < i, j +1> , < i+1, j > , < i, j -1> } , which are given by

V_M^{adj} ={(-1,0), (0,1), (1,0), (0,-1) } and diagonal neighbor cells { < i-1, j +1 > , < i+1, j +1> , < i+1, j - 1 > , < i-1, j -1> } given by the set

V_M^{diag} == {(-1,1), (1,1), (1,-1), (-1,-1) }

The 2D – CA evolves deterministically in discrete time steps, changing the states of all cells according to a local transition function $f{:}S^9 \rightarrow S$. The updated state of the cell < i, j > depends on the nine variables of the local transition function, which are the previous states of the cells constituting its neighborhood, that is :

$$a_{i,j}^{(t+1)} = f\left(a_{i+\alpha 1,j+\beta_1}^{(t)}, \ldots, a_{i+\alpha 9,j+\beta 9}^{(t)}\right)$$

The matrix $C^{(t)} = \begin{bmatrix} a_{0,0}^{(t)} & \cdots & a_{0,s-1}^{(t)} \\ \vdots & \ddots & \vdots \\ a_{r-1,0}^{(t)} & \cdots & a_{r-1,s-1}^{(t)} \end{bmatrix}$ is called the configuration at time t of the 2D – CA, and $C^{(0)}$ is the initial configuration of the CA. Moreover ,the sequence.$\{C^{(t)}\}_{0\le t\le k}$ is called the evolution of order k of the 2D – CA.

As the number of cells of the 2D – CA is finite; boundary conditions must be considered in order to assure the well defined dynamics of the CA. One constant several boundary conditions. But in this work, we will consider null boundary conditions:

If $(i,j) \notin \left\{ \begin{matrix} (u,v), \\ 0 \le u \le r-1, 0 \le v \le s-1 \end{matrix} \right\}, then \;\; a_{ij}^{(t)} = 0.$

A very important type of 2D – CA is linear 2D – CA, whose local transition function is as follows:

$$a_{ij}^{(t+1)} = \sum_{(\alpha,\beta)\in V_m} \mu_{\alpha\beta}\; a_{i+\alpha,i+\beta}^{(t)}$$

Where$\mu_{\alpha\beta} \in \mathbb{R}^+, and (\alpha,\beta) \in V_M$. Note that every CA endowed with a local transition function of the form given by (1), has an infinite state set :

$S = [0,\infty]$ Nevertheless, if finite state sets must be considered, for example,$S = \mathbb{Z}_k$

then a discretization function must be used with the local transition function as follow:

$$a_{i,j}^{(t+1)} = g\left(\sum_{(\alpha,\beta)\in V_m} \mu_{\alpha\beta}\; a_{i+\alpha,i+\beta}^{(t)}\right), with\; g{:}\,[0,\infty) \longrightarrow \mathbb{Z}_k$$

A. The C A Based Model for Spreading of Ocean Waves

The basic model

The basic model for spreading of waves based on a two – dimensional linear cellular automata with extended Moore neighborhoods, null boundary conditions and infinite sate set is described as follows.

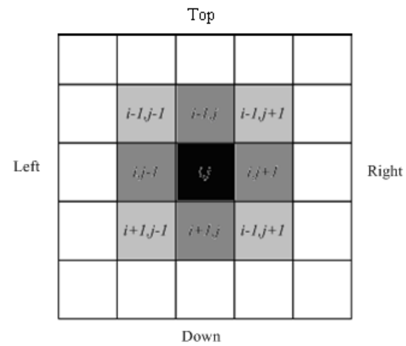

Figure 1.2. Two – dimensional linear cellular automata with extended Moore neighborhoods model

The waterfront in ocean can be interpreted as the cellular space of a 2D – CA by simply dividing it into a two dimensional array of identical square areas of side length L. Then each one of these areas corresponds to a cell of the CA (See Fig. 1.1). The State of a cell < i,j > at a time t, is defined as follows:

$a_{\text{ij}}^{(\text{t})} = \frac{traversed\;\; area\;\; of <i,j>}{total\;\; area\;\; of <i,j>}$ Consequently, $0 \le a_{ij}^{(t)} \le 1. if\; a_{ij}^{(t)} = 0$ then the cell < i,j > is said to be not traversed at time .t ; If $0 \le a_{ij}^{(t)} \le 1$ then the cell < i,j > is called partially traversed at time t ; and finally , if $a_{ij}^{(t)} = 1$, the cell is said to be completely traversed at time t.

The CA used in this model will be a linear CA. That is , the state of a cell <i,j> at any time (t + 1) depends on the states of its neighborhood cells at time t; More specifically, it can be expressed as

$$a_{ij}^{(t+1)} = \sum_{(\alpha,\beta)\in V_m} \mu_{\alpha\beta}\; a_{i+\alpha,i+\beta}^{(t)} \qquad (1)$$

Where $\mu_{\alpha\beta} \in \mathbb{R}^+$ are parameters involving some physical magnitudes of the cells As each cell of the CA, < i,j > represents as small square area of the ocean, then it is endowed with the three following parameters : the rate of spread of wave (R_{ij}), the wave speed (W_{ij}) and the height (H_{ij}).

The rate of spread of wave in < i,j >,(R_{ij}), determines the time needed for this cell to be completely traversed . It can be noted that if the cell < i,j > stands for waterless area, then $R_{ij} = 0, a_{\text{ij}}^{(\text{t})} = 0$ for every t.

The importance of this parameter lies in the fixing up of the size of the time teps, $\tilde{t}$ Suppose that the ocean is homogeneous, i.e., the value of the rate of wave spread is the same for all cells:

$R_{ij} \neq R, 0 \leq i \leq r-1, 0 \leq j \leq s-1$ Then, it is easy to check that if all cells in the neighborhood of < i,j > are not traversed at time t except only one adjacent neighbor cell, then the time needed for < i,j > to be completely traversed is $\frac{L}{R}$ (See Fig 2.1 (a))

Similarly, if all cells in the neighborhood of < i,j > are traversed at time t except only one diagonal neighborhood cell then the time needed for < i,j > to be completely traversed is $\sqrt{2}L/_{R}$

(See Figure 2.1(a), (b))

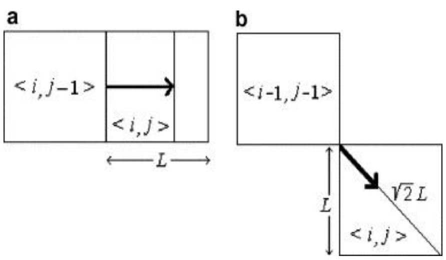

Figure 2.1. Propagation from a neighbor cell to the cell <i, j>

Thus, the size of time step is taken to be $\tilde{t} = \frac{L}{R}$

Consequently, if all cells in the neighborhood of < i,j > are not traversed at time t except only one adjacent cell which is completely traversed, then at time (t + 1) , the cell < i,j > is completely traversed : So,$a_{ij}^{(t+1)} = 1$. On the other hand, if the only completely traversed cell at time t is diagonal neighbor cell of < i,j >, then $a_{ij}^{(t+1)} = \lambda < 1$.

Nevertheless, almost all real oceans are non homogenous. In this case, the time step size is taken to be the time needed for the cells with the larger spread rate to be completely traversed. That is

$$\tilde{t} = \frac{L}{R}, R = max\{R_{ij}, 0 \leq r-1, 0 \leq j \leq s-1\} \quad (2)$$

Other factor to be incorporated to the model is the wave speed and direction due to its important influence to the spreading of waves.

The effects of the wave on a cell < i,j >, is given by the following 3 x 3 positive matrix ,called the wave matrix of < i,j >.

$$W_{ij} = \begin{bmatrix} w_{i-1,j-1} & w_{i-1,j} & w_{i-1,j+1} \\ w_{1,j-1} & 1 & w_{i,j+1} \\ w_{i+1,j-1} & w_{i+1,j} & w_{i+1,j+1} \end{bmatrix}$$ It can be observed that if no wave is propagation on < i,j >, then $w_{i+\alpha,j+\beta} = 1$ with $(\alpha,\beta) \in V_M$;

if ,for example , the wave is propagation from north towards south, then the coefficients $w_{i+1,j+1}, w_{i-1,j}$ *and* $w_{i-1,j+1}$ must be larger than the rest of the coefficients of W_{ij} and so on. The values of such coefficients stand for the magnitude of the wave.

Finally, the height differences between various points in the wave front also affect the spreading of waves. It is well known that waves show a higher rate of spread when they descend a downward slope and a smaller rate of spread when they climb up an upward slope. If H_{ij} stands for the height of the cell < i,j >, then H_{ij} is the height of the center point of the square area which is represented by the cell and it is supposed that this height is the same at every point of the cell. The effect of such parameter in the spreading of waves given by the following 3 x 3 matrix

$$\Phi_{ij} = \begin{bmatrix} h_{i-1,j-1} & h_{i-1,j} & h_{i-1,j+1} \\ h_{1,j-1} & 1 & h_{i,j+1} \\ h_{i+1,j-1} & h_{i+1,j} & h_{i+1,j+1} \end{bmatrix}$$ Where

$$h_{i+\alpha,j+\beta} = \boldsymbol{\Phi}\left(H_{ij} - H_{i+\alpha,j+\beta}\right) \text{ and } \boldsymbol{\Phi}$$

is usually taken to be a linear function.

As a consequence, if we incorporate All these parameters to the model defined by (2) , then

$$\mu_{\alpha\beta}\, w_{i+\alpha,j+\beta} h_{i+\alpha,j+\beta}, \ \forall\, (\alpha,\beta) \in V_M \quad (3)$$

and the evolution of the cell < i,j > is given by

$$a_{ij}^{(t+1)} = a_{ij}^{(t)} + \sum_{(\alpha,\beta)\in V_M^{adj}} \mu_{\alpha\beta}\ a_{i+\alpha,i+\beta}^{(t)} + \boldsymbol{\lambda} \sum_{(\alpha,\beta)\in V_M^{diag}} \mu_{\alpha\beta}\ a_{i+\alpha,i+\beta}^{(t)}$$

It may be remarked that, during the evolution of the CA, some cells can probably assume a state greater than 1. In these cases, the states must be taken to be equal to 1.

B. The New Model

In this work we propose that the propagation of waves from a diagonal neighborhood cells, for example < i-1,j-1 >, ;to ;the main cell < i,j >, is supposed to be circular,; as is shown in Figure.2.2

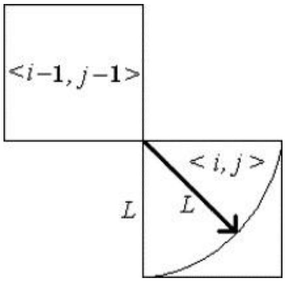

Figure.2.2. Propagation from a diagonal neighbor cell to the < i,j >

As a consequence, after a time step, the traversed area of < i,j > are not traversed at time t, except a diagonal neighbor, say < *i-1,j-1* >, which is completely traversed $a_{i-1,j-1}^{(t)} = 1$, then

$$a_{\mathrm{ij}}^{(\mathrm{t+1})} = \lambda = \frac{\pi L^2}{4L^2} = \frac{\pi}{4} \approx 0.785.$$

As a consequence, the transition function of the 2D – CA given by

$$a_{ij}^{(t+1)} = a_{ij}^{(t)} + \sum_{(\alpha,\beta)\in V_M^{adj}} \mu_{\alpha\beta}\ a_{i+\alpha,i+\beta}^{(t)}$$

$$+0.785 \sum_{(\alpha,\beta)\in V_M^{diag}} \mu_{\alpha\beta}\ a_{i+\alpha,j+\beta}^{(t)} \qquad (4)$$

Where $0 \le i \le r-1, 0 \le j \le s-1$. Note that the transition function is only valid for homogenous oceans. In the case of non homogenous ocean, the size of the time step is given by the expression (3) and consequently we have to incorporate a new factor in the transition function: the; rate of wave spread $R_{ij} = R$; If all neighborhood cells are not traversed at time t except only one adjacent cells, them after a time step the traversed area *of* < *i,j* > *is* $\frac{R_{ij} L^2}{R}$; Consequently, $a_{\mathrm{ij}}^{(\mathrm{t+1})} = {R_{ij}}/{R} < 1$. If the traversed neighbor cell is diagonal cell, then the traversed area of < i,j > after a time step is $\frac{\pi R_{ij} L^2}{4R^2}$ *and* $a_{\mathrm{ij}}^{(\mathrm{t+1})} = \frac{\pi R_{ij}^2}{4R^2}$.Further, this new fact is incorporated in the model ad follows:

$$a_{ij}^{(t+1)} = \frac{R_{ij}}{R} a_{ij}^{(t)} + \sum_{(\alpha,\beta)\in V_M^{adj}} \mu_{\alpha,\beta} \frac{R_{i+\alpha,j+\beta}}{R} a_{i+\alpha,i+\beta}^{(t)}$$

$$+ \sum_{(\alpha,\beta)\in V_M^{diag}} \mu_{\alpha\beta}\ a_{i+\alpha,i+\beta}^{(t)} \frac{\pi R_{i+\alpha,j+\beta}^2}{4R^2} a_{i+\alpha,i+\beta}^{(t)}$$

with $0 \le i \le r-1, 0 \le j \le s-1$

Moreover, it is also possible to incorporate, in a very simple manner, changes in both wave speed and direction. It can be modeled by simply varying the wave matrix involving time:

$$W_{ij} = \begin{bmatrix} w_{i-1,j-1}^{(t)} & w_{i-1,j}^{(t)} & w_{i-1,j+1}^{(t)} \\ w_{1,j-1}^{(t)} & 1 & w_{i,j+1}^{(t)} \\ w_{i+1,j-1}^{(t)} & w_{i+1,j}^{(t)} & w_{i+1,j+1}^{(t)} \end{bmatrix}$$

So, evolution of the cell the< i,j > with non constants wave Conditions given by

$$a_{ij}^{(t+1)} = \frac{R_{ij}}{R} a_{ij}^{(t)} + \sum_{(\alpha,\beta)\in V_M^{adj}} w_{i+\alpha,j+\beta}^{(t)}$$

$$+h_{i+\alpha,j+\beta}^{(t)} \frac{R_{i+\alpha,j+\beta}}{R} a_{i+\alpha,i+\beta}^{(t)}$$

$$+ \sum_{(\alpha,\beta)\in V_M^{diag}} w_{i+\alpha,j+\beta}^{(t)} + h_{i+\alpha,j+\beta}^{(t)} \frac{\pi R^2{}_{i+\alpha,j+\beta}}{4R^2} a_{i+\alpha,i+\beta}^{(t)} \quad (5)$$

Finally, we can discretize the states of energy ;cell of the 2D – CA in order to obtain a new 2D – CA with discrete state set. As our goal is to study the spread of the Wave front, we will consider a 2D – CA whose state set is

$S_{\in Z}$, by setting

$$s_{ij}^{(t)} = \begin{cases} 0, if\ 0 \le a_{ij}^{(t)} < 1 \\ 1, if\ \quad a_{ij}^{(t)} \ge 1 \end{cases} \text{ for } 0 \le i \le r-1, 0 \le j \le s-1$$

That is the local transition function is

$a_{ij}^{(t=1)} = g\left(\frac{R_{ij}}{R}\ a_{ij}^{(t)} + \cdots\right)$ Where g:[0,∞]⟶ℤ such that

$$t \longrightarrow g(t) = \begin{cases} 0, if\ 0 \le t < 1 \\ 1, if \quad\ t \ge 1 \end{cases}$$

III. VALIDATION OF THE PROPOSED MODEL

To check whether our model satisfies some tests, we will consider four basic tests, which are classified into two classes: homogeneous ocean tests and non homogeneous ocean tests. In both classes of tests, we must consider flats and non-flat oceans weather conditions (wave speed and direction).

If a homogeneous flat ocean with wave conditions is considered, the model must yield a circular wave front. If there are some weather conditions,; the wave speed and direction must effect the ocean wave front. Furthermore, if the homogeneous ocean is non-flat, the topographic conditions must be reflected in the dynamic of wave front since, as is mentioned earlier, waves show a higher rate of spread when they descend a downward slope and a smaller rate of slope when they climb up an upward slope.

On the other hand, if the ocean is non homogeneous, the wave front must be of circular shape. It advances with the same speed in all directions, in the areas whose rate of wave spread is equal to R (See equation (4)); and this speed must decrease in the areas with another rate of wave spread.

An algorithm using the java language has been implemented for the computational and graphical represented of the wave fronts. The hypothetical models used are modeled by means of a bi dimensional array of 1024 x 1024 cells. In the initial configuration, there is a circular traversed area of radius 10 whereas the rest cells are not traversed, and 500 evolutions of the cellular automata are calculated.

In the following figures, only the wave fronts at times t = 10 k, with $k_{\in Z}$,$0 \leq k \leq 50$ are shown.

First of all, suppose that the ocean is spreading in a hypothetical homogenous ocean, then

$R_{ij} = R_{\in Z}$ for every *(i,j.)*

If the Ocean is flat and no wave is propagation, then one can suppose that

$$\Phi_{ij} = \begin{bmatrix} h & h & h \\ h & 1 & h \\ h & h & h \end{bmatrix} = W_{ij} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}, \text{where}$$

$h_{\in Z}$, $0 \leq i \leq 1023, 0 \leq j \leq 1023$

and for the sake of simplicity, we can also consider h = 1. In this case, the wane front is circular as is shown in Figure 3.1

Now suppose that the ocean is non-flat and there is wave propagation according to the following matrices:

$$\Phi_{ij} = \begin{bmatrix} 1.5 & 1 & 0.5 \\ 1.5 & 1 & 0.5 \\ 1.5 & 1 & 0.5 \end{bmatrix} = W_{ij} = \begin{bmatrix} 0.5 & 0.5 & 0.5 \\ 1 & 1 & 1 \\ 1.5 & 1.5 & 1.5 \end{bmatrix}$$

with $0 \leq i \leq 1023, 0 \leq j \leq 1023$.

Then, the evolution of the wave front is shown in Figure 4.2

Finally, in Figure 4.1 the evolution of the ocean wave front without weather and topographic condition of homogeneous ocean is shown. If the wave is propagation and the front in non-flat, then according to (5), the evolution of the wave front is shown in Figure 4.2.

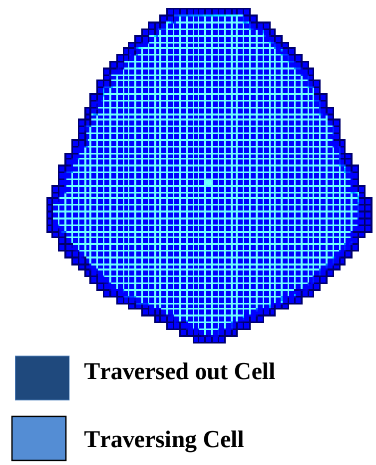

Figure 3.1. A Tsunami wave front a new cell state

IV. THE PROPOSED MODEL SIMULATION RESULTS

If a homogeneous flat ocean with wave conditions is considered, the model must yield a circular wave front. In some weather conditions, the wave speed and direction must affect the ocean wave front. Furthermore, if the homogeneous ocean is non-flat, the topographic conditions must be reflected in the dynamic of wave front since, as is mentioned earlier, waves show a higher rate of spread when they descend a downward slope and a smaller rate of slope when they climb up an upward slope.

A. Homogeneous Ocean Test

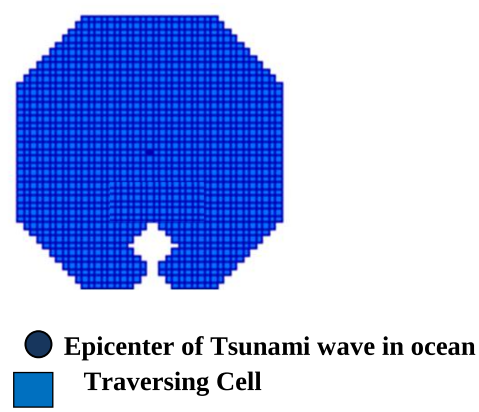

Figure 4.1.Homogeneous simulation results

B. Non- Homogeneous Ocean Test

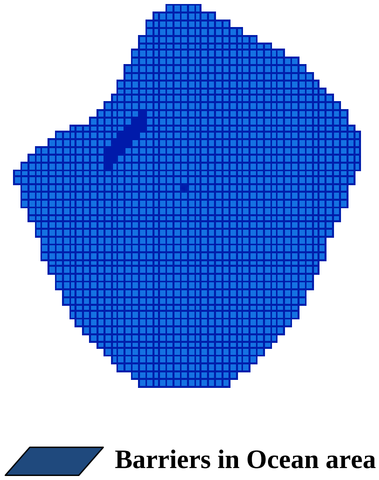

Figure 4.2 Non-.Homogeneous simulation results

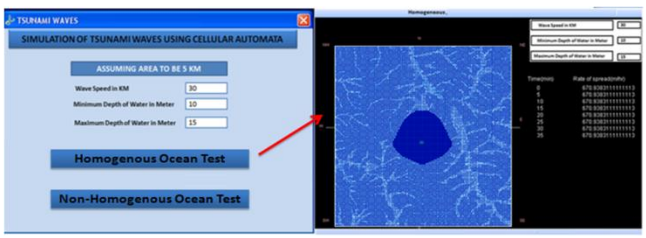

Figure 4.3.User Interface of the Tsunami Wave Simulation Model platform

V. CONCLUSION AND FUTURE WORK

In this work, a CA based model for the study of the dynamic of a Tsunami Wave front has been presented. Basically we have proposed a circular spreading of the wave front, when it comes from a diagonal cell. The model determines the dynamic of the wave front in both homogenous and non homogeneous oceans with weather and based topography conditions. Moreover, several tests have been checked in order to determine the goodness of ht e proposed method.

Further work may be aimed at designing a Hexagonal cellular automata based model to simulate the Tsunami wave propagation. Moreover, some changes in the notion of the state of the cell can be studied. In this sense, a similar CA model will be designed in which the stats of the cell will be defined by means of transfer of energy, instead of the transfer of fractional traversed area.

Furthermore, due to the fact that the behavior of some discrete models has discrepancies with the corresponding conditions model, it will be of interest to study how to decrease these discrepancies. Then further works to be considered are.

1. Consider new temporal coordinates and not only spatial coordinates.
2. Study the influence of new variables, like magnitude of wave, in wave propagation.
3. Finally, it will be interesting to explore other cases using probabilistic updating rules.

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