Tsunami Wave Propagation Models based on Two-Dimensional Cellular Automata

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ABSTRACT

Tsunami is a natural disaster which can cause great economic losses and make eco-environment seriously disordered. As of today, no technology exists to predict a tsunami source event well in advance. In this paper, some physically realistic ocean parameters have been considered. For tsunami propagation in real-time simulation, approaches have been used and different modifications of well known tsunami propagation models are developed to explore the sensitivity of the computational results to the variation of major model parameters. The tsunami waves are divided into two categories and our models are applied to eight cases depending on homogenous and non-homogeneous ocean wave conditions for different rates of spread. The algorithm is efficient and easily implemented, allowing less computational time and cost. The results obtained are found to be in agreement with the results of tsunami wave propagation in real seas. The first part of the paper describes the structure of the system, the underlying cellular automata models and the final part shows the activation of the system and the calculated results.

Key words: Tsunami wave, Simulation, homogeneous, Non-homogeneous, Cellular automata

1. INTRODUCTION

A common approach in modeling the propagation of tsunami is based on the assumption of a kinematic vertical displacement of ocean water that is analogous to the ocean bottom displacement during a submarine earthquake and the use of a non-dispersive long-wave model to simulate its physical transformation as it radiates outward from the source region. [10].

Once the tsunami is generated, its propagation is influenced by the depth of the ocean. Both the wave amplitude and energy increase significantly toward the shoreline [7].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 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]

The problem of tsunami propagation is a special case of the general water-wave problem. The study of water waves relies on several common assumptions. If a Tsunami of initial height propagates from a point source and a constant water depth is considered, the wave amplitude at distance R is proportional to the inverse of the distance and proportional to the initial height.

This means that the height cannot be higher that the initial height and reduces along the distance. [1] [11].The error made on the initial condition cannot be corrected by the numerical method used to propagate the tsunami. During an earthquake, one side of the fault moves vertically and/or horizontally with respect to the other side. The amount of slip throughout the rupture area of an earthquake has the largest influence on the size of the local tsunami [4][5].The size of the local tsunami waves also depends on how deep the earthquake ruptured within the earth [4].

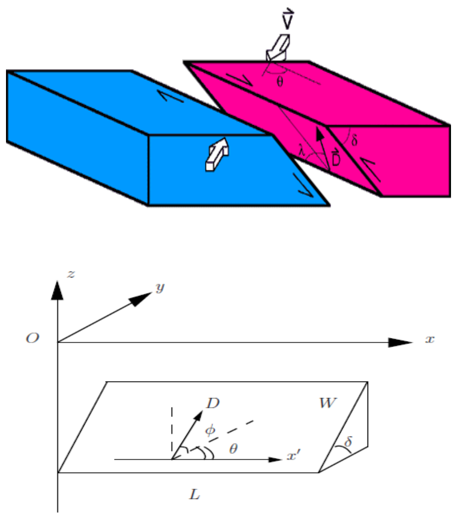

Figure 1: Geometry of the source model (dip angle δ, depth df , length L, width W) and orientation of Burger's vector D (rake angle θ, angle φ between the fault plane and Burger's vector).

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 [9][16]
In their review paper, Dutykh and Dias [2] generated waves theoretically by multiplying the static deformations caused by slip along a fault by various time laws [6]
Some factors to be considered in random order for geometry of source model are the following:
a) Depth at which the slide occurs, or rather, depth of water above slide.
b) Angle of the slide from the horizontal (or vertical) direction.
c) Characteristic speed with which the slide moves. [12][14]

In the open ocean a tsunami is less than a few feet high at the surface, but its wave height increases rapidly in shallow water. But, as the tsunami reaches shallower coastal waters, wave height can increase rapidly [15] [17] one moving toward the deep ocean and another moving toward the local

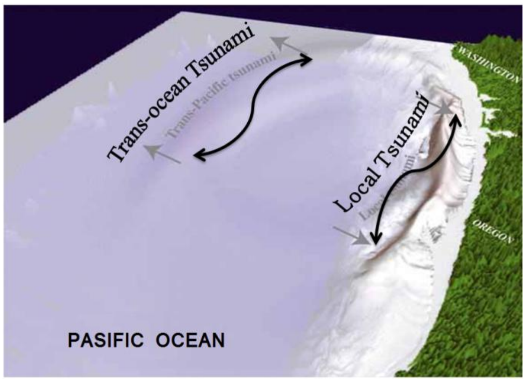

Figure 2. Trans-ocean tsunami waves

shoreline (U.S. Geological Survey Professional Paper 1661-B). 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 epicentral area. Second, an ocean-wide tsunami is one which propagates throughout the ocean in which it is generated, but the loss of life and damage are mostly confined to the epicentral area [13]
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. Both of the secondary wave fronts initially travel parallel to shoreline, but their paths of travel curve (refract) toward shore.

Physics tells us that when the energy in a system remains constant, but velocity decreases, the mass in the system must increase. A slower moving tsunami is a physically higher tsunami. The waves scrunch together like the ribs of an accordion and heave upward. [3]

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

2. BACKGROUND ON TWO DIMENSIONAL CELLULAR AUTOMATA (CA)

CAs consisting of four basic units, including cells, cell space, neighbors and rules. As well as the cell state. According to specific rules, cell state will change from time to time.
CAs can be any dimension in theory. The article used a two-dimensional CA, named Moore neighborhood. In this case of the neighborhood of the (i,j) cell consists of the (i,j) cell itself and of all eight cells which are adjacent and diagonal to it. . For each cell we define 8 major spread directions (propagation lines) N, NE, E, SE, S, SW, W, and NW as shown in Figure 3.

The smaller of this value, the more clearly of the details of spread of waves, but that will increase the quantity of computation and data, slowing down the simulation speed.
We represent a tsunami as a two-dimensional cell-space composed of cells of dimensions ℓ and b , where ℓ and b are the length and breadth of the cell, respectively This allows for the computation of wave spread in only the specified major directions instead of all directions and thus, significantly reduces wave spread computation time.

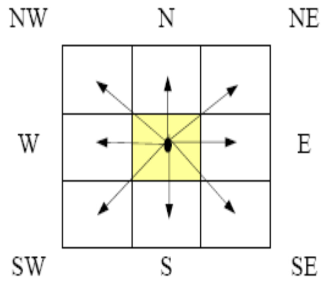

Figure 3. Potential neighbor cells of Moore neighborhood from center cell

NW4	NW7	NW8	NNN	NE8	NE7	NE4
NW5	NW1	NW3	NN	NE3	NE1	NE5
NW6	NW2	NW	N	NE	NE2	NE6
WWW	WW	W	C	E	EE	EEE
SW6	SW2	SW	S	SE	SE2	SE6
SW5	SW1	SW3	SS	SE3	SE1	SE5
SW4	SW7	SW8	SSS	SE8	SE7	SE4

Figure 4. ''Extended'' Moore neighborhood, i.e. the Moore neighbourhood formed by (i, j) cell and its eight neighbors, is extended to a 7 X 7 cell neighborhood.

The present work proposes a "extended'' Moore neighborhood model for spreading of waves based on two-dimensional cellular automata. We choose this mathematical model, which is very easy to implement in software and in hardware.

For this, we divide a wave front in ocean into two dimensional arrays a way of identical square areas; each one of them stands for a cell of the 2D – CA. The states considered are 0 if the cell is not traversed or partially traversed and 1 if the cell is fully traversed. Further, the state of every cell evolves taking into account the states of eight nearest cells and its own state at a preceding time.

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 $A = (d, p, u, q)$, where C is the cellular space formed by a two- dimensional array of r x p identical objects called cells: $D=\{<i,j>, 0 \le i \le r-1, 0 \le j \le p-1\}$ such that each of them can assume a state. The state of each cell is an element of a finite or infinite state set, P; if P is finite and $|P| = k$ then S is taken to be $S_k = \{0,1,2,...,k-1\}$ .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 $U \subset S \cup S, |U| = M$, such that for every cell < i , j >, its neighborhood U_{ij} is the ordered sets of m cells given by

$$\{<i+\alpha_1, j+\beta_1>, ..., <i+\alpha_M, j+\beta_M> : (\alpha_M, \beta_M) \in U\}.$$

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:

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

Graphically the extended Moore neighborhood of a cell <i, j > can be seen as follows:

< 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>

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 U_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 U_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 $f: P^9 \to P$. 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:

$$a_{i,j}^{(t+1)} = q\left(a_{i+\alpha_1, j+\beta_1}^{(t)}, ..., a_{i+\alpha_9, j+\beta_9}^{(t)}\right)$$

The matrix $D^{(t)} = \begin{pmatrix} a_{0,0}^{(t)} & \cdots & a_{0,p-1}^{(t)} \\ \vdots & \ddots & \vdots \\ a_{r-1,0}^{(t)} & \cdots & a_{r-1,p-1}^{(t)} \end{pmatrix}$ is called the configuration at time t of the 2D – CA, and $D^{(0)}$ is the initial configuration of the CA. Moreover the sequence $\{D^{(t)}\}_{0 \le t \le k}$ 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 are proved. But in this work, we will consider null boundary conditions:

If $(i,j) \notin \{(u,v), 0 \le u \le r-1, 0 \le v \le p-1\}$, then $a_{ij}^{(t)} = 0$.A very important type of 2D – CA is linear 2D– CA, whose local transition function is as follows:

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

where $\mu_{\alpha\beta} \in \mathbf{R}^+$ and $(\alpha,\beta) \in U_M$. Note that every CA endowed with a local transition function of the form given by (1), has an infinite state set: $P = [0,\infty)$ Nevertheless, if finite state sets must be considered, for example, $P = S_k$ then a discretization function must be used with the local transition function as follows:

$$a_{ij}^{(t+1)} = g\left(\sum_{(\alpha,\beta)\in U_M} \mu_{\alpha\beta} a_{i+\alpha, j+\beta}^{(t)}\right),$$

with $g: [0,\infty) \to S_K$.

2.1 The Cellular Automata Based Model for Spreading of Ocean Waves

2.1.1 The model

The 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

The wave front 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 Figure 3). The state of a cell < i, j > at a time t, is defined as follows:

$$a_{ij}^{(t)} = \frac{Traversed\ area\ of < i,j >}{Total\ area\ of < i,j >}$$

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 $0 < a_{ij}^{(t)} < 1$ 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

$$a_{ij}^{(t+1)} = \sum_{(\alpha,\beta)\in U_M} \mu_{\alpha\beta} a_{i+\alpha,j+\beta}^{(t)} \qquad (2)$$

where $\mu_{\alpha\beta} \in \mathbf{R}^+$ 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 $R_{ij} = 0, a_{ij}^{(t)} = 0$ for every t.

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

$R_{ij} = R, 0 \le i \le r-1, 0 \le j \le p-1$ 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 $\frac{L}{R}$ .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 $\frac{\sqrt{2}L}{R}$ (See Figure 5)

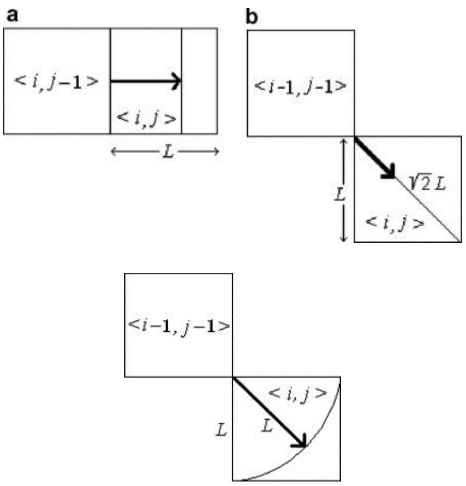

Figure 5.Propagation from a neighbor cell to the cell<1, j>

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

$$\tilde{t} = \frac{L}{R}, R = max\{R_{ij}, 0 \le i \le r-1, 0 \le j \le p-1\} \qquad (3)$$

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 >.

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

It can be observed that if no wave is propagated on < i, j >, then $W_{i+\alpha,j+\beta} = 1$ with $(\alpha,\beta) \in U_M$; 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 local tsunami and a smaller rate of spread when they climb up trans-ocean wide tsunami. 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

$$\gamma_{ij} = \begin{pmatrix} h_{i-1,j-1}^{(t)} & h_{i-1,j}^{(t)} & h_{i-1,j+1}^{(t)} \\ h_{1,j-1}^{(t)} & 1 & h_{i,j+1}^{(t)} \\ h_{i+1,j-1}^{(t)} & h_{i+1,j}^{(t)} & h_{i+1,j+1}^{(t)} \end{pmatrix}$$

where $h_{i+\alpha,j+\beta} = \gamma(H_{ij} - H_{i+\alpha,j+\beta})$ and γ is usually taken to be a linear function. As a consequence, if we incorporate all these parameters to the model defined by (2), the

$$\mu_{\alpha\beta} = w_{i+\alpha,j+\beta} h_{i+\alpha,j+\beta}\ ,\ \forall\ (\alpha,\beta) \in U_M \qquad (4)$$

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

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

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. 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:

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

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

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

$$+\sum_{(\alpha,\beta)\in U_M^{dia}}\left(w_{i+\alpha,j+\beta}^{(t)}+h_{i+\alpha,j+\beta}\right)\frac{\pi R^2_{i+\alpha,j+\beta}}{4R^2}a_{i+\alpha,j+\beta}^{(t)}$$

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 2D – CA whose state set is $P=S$,by setting $P_{ij}^{(t)}=0, 0\le a_{ij}^{(t)}<1, P_{ij}^{(t)}=1, a_{ij}^{(t)}\ge 1$ for

$0\le i\le r-1, 0\le j\le p-1$

That is the local transition function where g: $[0,\infty)\to S$,

such that $t\to g(t)=0, 0\le t<1$

3. TESTING 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 horizontal and vertical wave front conditions in ocean of wave speed and direction.

If the homogeneous ocean with horizontal wave conditions is considered, the model must yield a circular wave front. If there are some weather conditions, the wave speed and direction must affect the ocean wave front. Furthermore, if the homogeneous ocean with vertical wave motions, the topographic conditions must be reflected in the dynamic wave front since, as is mentioned earlier, waves show a higher rate of spread when they descend along local tsunami waves and a smaller rate of slope when they climb up a trans-ocean tsunami waves (Refer Figure 2).

On the other hand, if the ocean is non homogeneous, the wave front must be of circular shape in the initial condition . It advances with the same speed in all directions, in the areas whose rate of wave spread is equal to R 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 representation of the wave fronts. The hypothetical models used are modeled by means of a two dimensional array of 512 X 512 cells. In the initial configuration, there is a circular traversed area of radius 10 units whereas the remaining cells are not traversed, and 250 evolutions of the cellular automata are calculated. In the following equations, only the wave fronts at times t = 10 k, with $k\in S$, $0\le k\le 50$ are shown. First of all, suppose that the ocean is spreading in a hypothetical homogenous ocean, then

$R_{ij}=R\in S$ for every i, j.

If the ocean is horizontal wave motion and no wave is propagated, then one can suppose that

$$\gamma_{ij}=\begin{pmatrix}h&h&h\\h&h&h\\h&h&h\end{pmatrix}, W_{ij}=\begin{pmatrix}1&1&1\\1&1&1\\1&1&1\end{pmatrix},$$

where $h\in S, 0\le i\le 511, 0\le j\le 511$ and for the sake of simplicity, we can also consider h = 1. In this case, the wave front is circular.

Now suppose that the ocean is having vertical wave motions and there is wave propagation according to the following matrices

$$\gamma_{ij}=\begin{pmatrix}1.5&1&0.5\\1.5&1&0.5\\1.5&1&0.5\end{pmatrix}, W_{ij}=\begin{pmatrix}0.5&0.5&0.5\\1&1&1\\1.5&1.5&1.5\end{pmatrix}$$

with $0\le i\le 511, 0\le j\le 511$.Finally, suppose that the tsunami wave is spreading in an non homogeneous environment, where the rates of spreading are as follows:

$$R_{ij}=\begin{cases}1, \text{ if } 0\le i\le 255, & 0\le j\le 511\\ 3, \text{ if } 256\le i\le 511, & 0\le j\le 255\\ 4.5, \text{ if } 256\le i\le 511, & 256\le j\le 511\end{cases}$$

4. SIMULATION RESULTS OF THE PROPOSED MODEL

4.1 Homogeneous Ocean

4.1.1 Homogeneous Ocean, Horizontal Wave Motion with Primary Wave Front

In the case of horizontal wave motion, the spread is even and with Primary wave front, the spread is even in all directions as shown in the Figure 6.

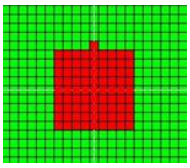

Figure 6.Homogeneous, Horizontal with Primary wave front and direction

4.1.2 Homogeneous Ocean, Horizontal Wave Motion with Secondary front

In this case, from the central cell, the neighboring cells are partially traversed, and then they are completely traversed, in the specified direction. The spread is even and with varying wave direction, the spread is more in the specified direction as shown in Figure 7.

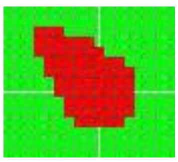

Figure 7. Homogeneous, Horizontal wave motion with Secondary wave front and direction in North-West

4.1.3 Homogeneous Ocean, Vertical Wave Motion with Primary Wave Front

In this case of vertical wave motion, the spread is very fast in the trans-ocean tsunami wave direction, moderate on the side direction, if the waves are slow down in the local tsunami wave direction. With Primary wave front, the spread is even as shown in the Figure 8.

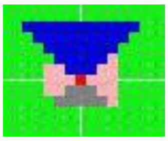

Figure8. Homogeneous, vertical wave motion with Primary wave front

4.1.4 Homogeneous Ocean, Vertical Wave Motion with Secondary Wave Front

In this case, from the central cell, the neighboring cells are partially traversed and then they are completely traversed, in the specified direction. In vertical wave motion, the spread is very fast in the trans-ocean wave direction, moderate in the sides of the ocean and slow in local tsunami wave direction. With varying wave directions, the spread is more on the specified direction; the spread is shown in the Figure 9.

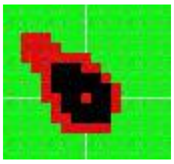

Figure9. Homogenous Tsunami, Vertical wave motion with Secondary wave front in North-West

4.1.5 Rate of Spread

Here, Two-dimensional Square cellular automata for homogeneous oceans with horizontal wave motion and constant wave. From this Condition, it is found that the rate of spread is constant for both the cases, as there are same types of tsunamis throughout the ocean.

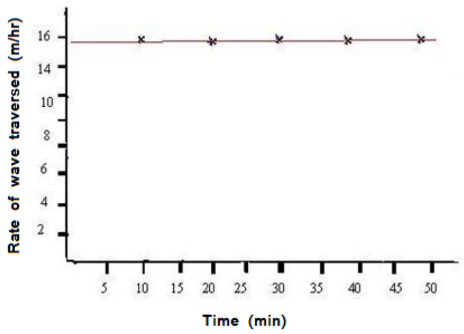

Figure10. Rates of wave traverse between Two-dimensional square CA Homogeneous ocean waves.

4.1.6 Number of Cells Traversed

The number of cells traversed in Two-dimensional Square cellular automata for homogeneous Tsunamis with horizontal wave motion and constant wave.

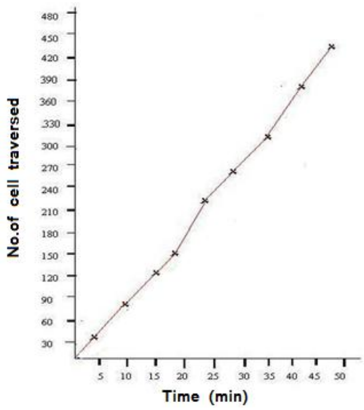

Figure 11. No. of cells traversed in Two-dimensional square CA homogeneous ocean.

4.2. Non Homogeneous Ocean Tests

4.2.1 Non-Homogeneous Ocean, Horizontal Wave Motion with Primary Wave Front

In the case of horizontal wave motion, the wave traversed is even and with Primary wave front, the traversed is even in all directions; which is shown in the Figure12.

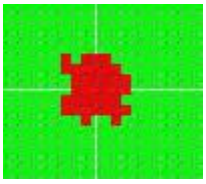

Figure 12. Non-homogenous Ocean, horizontal wave motion with Constant wave

4.2.3 Non Homogeneous Ocean, Horizontal Wave Motion with Secondary Wave Front

In this case of horizontal wave motion, the wave traversed is even and with varying wave direction, the traversed is more in the specified direction, which is shown in the Figure 13.

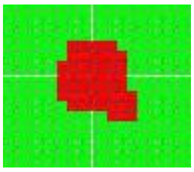

Figure13. Non-homogenous Ocean, horizontal wave motion with Secondary wave front in South-West

4.2.2 Non-Homogeneous Ocean, Vertical Wave Motion with Primary Wave Front

In the case of vertical wave motion, the wave traversed is very fast in the trans-ocean tsunami wave direction, moderate in the sides of the ocean and slow down in local tsunami wave direction with Primary wave front, the wave traversed is even; which is shown in the Figure 14.

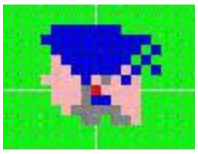

Figure 14. Non-homogenous Ocean, Vertical wave, Primary wave front

4.2.3 Non-Homogeneous Ocean, Vertical Wave Motion with Secondary Wave Front

In the case of vertical wave motion, the wave traversed is very fast in the trans-ocean tsunami wave direction, moderate in the sides of the ocean and slow down in the local tsunami wave direction. With varying wave direction, the traversed is more in the specified direction; which is shown in the Figure 15.

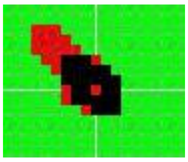

Figure 15. Non-homogenous ocean, vertical wave motion with secondary wave front in North-West

4.2.4 Rate of Spread

The rate of spread in two-dimensional square cellular automata for non-homogeneous ocean is horizontal wave motion and constant wave. From the graph it is seen that the rate of spread is nearly constant which is not accurate for any non-homogeneous ocean of tsunamis.

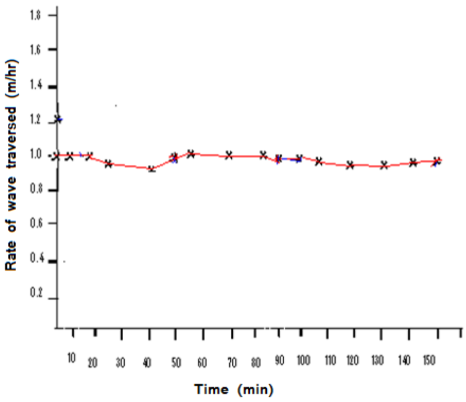

Figure 16. Rate of spread in Two-dimensional Square CA in non-homogeneous ocean.

4.2.5 Number of Cells Traversed

Here, the number of cells traversed in two-dimensional square cellular automata for non-homogeneous ocean with horizontal wave motion in constant wave. It is seen that the number of cells traversed in Two-dimensional square model is more, even though the area of the cells is less. But in our result, the area of the cells is more and the number of cells traversed is less, which is more accurate.

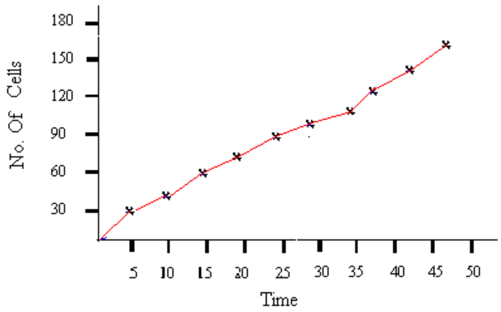

Figure 17. No. of cells traversed Two-dimensional square CA in non-homogeneous ocean.

5. CONCLUSION

In this work, a two dimensional cellular automata model for the prediction of tsunami wave spreading has been introduced. It is based on the horizontal and vertical wave motion in ocean topography conditions. The states of each cell are well defined by means of transfer of fractional traversed area. Also, different rates of speed are considered. The algorithm seems to be very efficient and it is easily implemented in any computer system, allowing a low computational cost.

The two dimensional cellular automata model is applied to eight cases depending on the wave, topography and speed conditions. All the graphical models obtained are found to be in agreement with the experience of wave spreading in real Tsunamis.

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