Tsunami Prediction and Estimation System using Markov Chain Method

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ABSTRACT

Determining the likelihood of a disaster is a key component of any comprehensive hazard assessment. Tsunami is a natural disaster, which is usually caused by a severely disturbance happening undersea or activity in the ocean or near the coast. It leads to a series of large waves with very long wavelength and period as well as is a result of a large-scale vertical displacement of the sea over a short duration in time. This paper presents a model that will predict whether tsunami can occur at the specific coordinate that executes based on 100 years tsunami history data. The main contribution of this paper is that the Markov chain approach is used for prediction model based on probabilities at a time interval depending upon the value of the number at the previous time. The method also uses specific action to predict and is aimed specially for calculating the tsunami potential.

Keyword: Tsunami, Markov chain, Prediction, Probability

1. INTRODUCTION

The tsunami is the most formidable of all natural hazards. Most tsunamis are caused by vertical displacements of the seafloor associated with the occurrence of great earthquakes. Tsunamis can also be generated by submarine volcanic eruptions, by the movement of submarine sediments, by coastal landslides, and even by meteor impacts. The time lapsed between the generation of tsunami and arrival to coastline is very short. There is no direct confirmation of the size of a tsunami until it reaches the shoreline. The interval between the moment of wave generation in the ocean and the arrival of the tsunami on the coast (from 20 min to a few hours) was sufficient to evacuate people from the possible flooding zone, but the absence of an early warning system in this region meant that timely evacuation was impossible. So advanced notification is important. There is a need to develop advanced probabilistic approaches, capable of exploiting jointly data of different nature, such as tsunami data and, in addition, the databases of earthquakes, of volcanic eruptions, and, where available, of the submarine landslides.

2. RELATED WORK

In Japan, an integrated simulation system for prediction of earthquake and tsunami disasters is developed. For reliable prediction advanced computer simulation is combined with real-time observed data from nation-wide seismic and GPS networks [6]. Eric L. Geist and Tom Parsons discuss probabilistic tsunami hazard analysis (PTHA) from the standpoint of integrating computational methods with empirical analysis of past tsunami runup [2]. S. MARETZKI, S. GRILLI, and C. D. P. BAXTER presents results of a probabilistic analysis that estimates the hazard, expressed in terms of runup (at a given probability of occurrence), of submarine mass failures (SMF) tsunamis triggered by earthquakes, on the upper northeast coast of the United States. A Monte Carlo approach is employed [3].

3. THE PROPOSED MODEL

In this paper, finite-state first order Markov chain is used to predict the tsunami potential. The system can be described by a set of finite states and that the system can be in one and only one state at a given time. The transition probability P_{ij}, the probability of transition from state i to state j, is given from every possible combination of i and j (including i = j) and the transition probabilities are assumed to be stationary (unchanging) over the time period of interest and independent of how state i was reached and either the initial state of the system or the probability distribution of the initial state is known [1].

3.1. Markov Chain

In this section, we will explain briefly Markov chain model using the prediction model. A Markov chain is a sequence X_1, X_2, X_3, ... of random values whose probabilities at a time interval depends upon the value of the number at the previous time. The range of random variables, i.e., the set of their possible values, is called the state space, the value of X_n being the state of the process at time n [7].

$Pr(X_{n+1} = x \mid X_n = x_n, \ldots, X_1 = x_1, X_0 = x_0)$
$= Pr(X_{n+1} = x \mid X_n = x_n)$

In Markov Decision Process (MDP), after observing the state of the process, an action must be chosen. The total number of actions is assumed finite A, the set of all possible actions. If the process is in state i at time n and action a is chosen, then the next state of the system is determined according to the transition probabilities $P_{ij}(a)$ [5]. $P(X_{n+1} = j \mid X_0, a_0, X_1, a_1, \ldots, X_n = i, a_n = a\} = P_{ij}(a)$

Thus, the transition probabilities are functions only of the present state and the subsequent action.

3.2. Tsunami Prediction Model

In this section, we present a simple Markov chain model of prediction tsunami potential. The state of the Markov chain corresponds to whether tsunami occur or not. So, the state space is comprised of two possible states, i.e. S = {x_1, x_2}. Their semantics are:

x_1 = tsunami occurs and

x_2 = tsunami does not occur.

Similarly, the total number of actions is assumed finite |A|; actions are chosen and executed from a subset $A(s_t) \subseteq A$. We can define tsunami's actions as

A = {earthquake, volcano eruption, other}.

Other actions are described in table 1.

Code	Action that caused Tsunami
0	Unknown cause
1	Earthquake
2	Questionable Earthquake
3	Earthquake and Landslide
4	Volcano and Earthquake
5	Volcano, Earthquake and Landslide
6	Volcano
7	Volcano and Landslide
8	Landslide
9	Meteorological
10	Explosion
11	Astronomical Tide

Table. 1. Action that caused Tsunami

To completely specify the model, the initial state or probability distribution of the initial state of the system $p(0) = [p_1, p_2, \ldots p_n]$ and the transition probability matrix P must specify. For example, the initial state of prediction tsunami potential for year 2004 in Indonesia can be defined by:

$$\begin{matrix} x_1 & x_2 \\ [0.49 & 0.51] \end{matrix}$$

that is calculated based on 100 years history data.

Probability transition table by action "earthquake" is given by

$$\text{To state} \quad x_1 \quad x_2$$
$$\text{From state} \begin{matrix} x_1 \\ x_2 \end{matrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

Here, P_{ij} represents the constant probability of transition from state $X_i(t)$ to state $X_j(t + 1)$ for any value of time t.

We have now defined a first order Markov process consisting of :

states : Two states – tsunami occur and no tsunami occur.

vector : Defining the probability of the system being in each of the states at time 0.

state transition matrix : The probability of the tsunami potential given the previous tsunami condition.

Given the initial distribution P(0),

$P(1) = P(0) . P$

$$= \begin{bmatrix} 0.49 & 0.51 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5834 & 0.4166 \end{bmatrix}$$

$P(2) = P(1) . P = P(0) . P . P = P(0) . P^2$

$$= \begin{bmatrix} 0.5834 & 0.4166 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5516 & 0.4484 \end{bmatrix}$$

$P(3) = P(2) . P = P(0) . P . P . P = P(0) . P^3$

$$= \begin{bmatrix} 0.5516 & 0.4484 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5624 & 0.4376 \end{bmatrix}$$

$P(4) = P(3) . P = P(0) . P . P. P . P = P(0) . P^4$

$$= \begin{bmatrix} 0.5624 & 0.4376 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5588 & 0.4412 \end{bmatrix}$$

$P(5) = P(4) . P = P(0) . P . P. P . P. P = P(0) . P^5$

$$= \begin{bmatrix} 0.5588 & 0.4412 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5600 & 0.4400 \end{bmatrix}$$

$P(6) = P(5) . P = P(0) . P . P. P . P. P. P = P(0) . P^6$

$$= \begin{bmatrix} 0.5600 & 0.4400 \end{bmatrix} \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

$$= \begin{bmatrix} 0.5596 & 0.4404 \end{bmatrix}$$

Thus, for any k,

$P(k) = P(0). P^k$

The elements of P must satisfy the following conditions:

$\sum_{j=1} P_{ij} = 1$ for all i and $P_{ij} >= 0$ for all i and j. Finally the system reaches equilibrium (often referred to as the steady state) which means the transitions between states do not take place. They do but they balance out so that the number in each state remains the same. To calculate the steady state, we have

$$[\, x_1 \quad x_2 \,] = [\, x_1 \quad x_2 \,] \begin{bmatrix} 0.41 & 0.59 \\ 0.75 & 0.25 \end{bmatrix}$$

and $x_1+x_2=1$. Hence we have three equations which we can solve.

Adopting the algebraic approach,

$x_1 = 0.41x_1 + 0.75x_2$

$x_2 = 0.59x_1 + 0.25x_2$

$x_1 + x_2 = 1$

Rearranging the first two equations,

$0.59x_1 - 0.75x_2 = 0$

$0.59x_1 - 0.75x_2 = 0$

$x_1 + x_2 = 1$

By solving, $x_1 = 0.56$ and $x_2 = 0.44$. Hence, in long run, tsunami potential will be 56%.

Figure 1 shows the potential probability of tsunami for Indonesia with bar chart. According to the observation, year 2004 to 2007 occurred tsunami in Indonesia. If the prediction probability is greater than 0.5, we will deduce that there will be tsunami at that year. Otherwise, there will not be tsunami. So we can conclude that tsunami prediction model using Markov Chain method is sufficiently accurate. Figure 2 shows the prediction probability data for India. In India, only year 2000 and 2002 caused the tsunami by the observation.

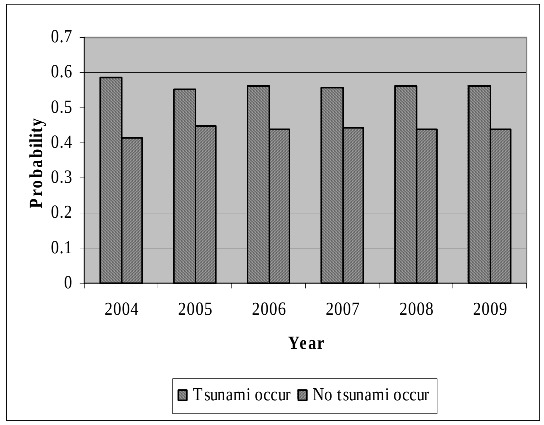

Figure. 1. Probability of tsunami potential for Indonesia

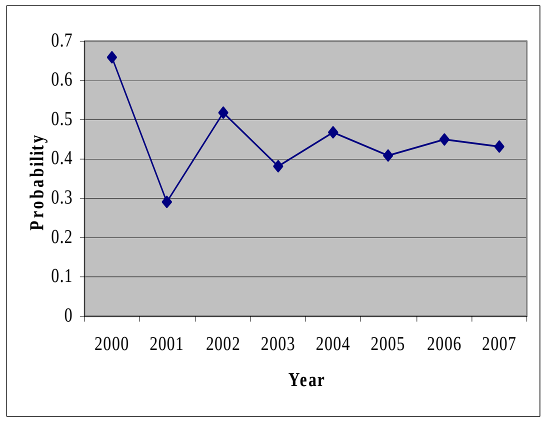

Figure. 2. Prediction probability data for India

3.3. Tsunami Prediction Algorithm

Tsu-predict (x, y, year, A)
begin
    Extract history tsunami data for specific coordinate (x, y);
    Compute the probability for specific action A by Prob (x, y, year, A);
    Display the result;
end

Prob (x, y, year, A)
begin
    Filter the past 100 year tsunami history data caused by A;
    Extract history data for A at specific coordinate;
    Find transition probability matrix;
    Specify the initial state P(0);
    Estimate the probabilities for specific year;
End

4. SYSTEM EVALUATION

4.1. The Transition Probability Matrix (TPM) Model

The model is referred to as a transition probability matrix (TPM) which generates synthetic sequences of annual tsunami potential. The probabilities for tsunami in one class to be followed by tsunami on the next year in the same or another class are collected into a matrix that is the Transition Probability Matrix (TPM). In the Transition Probability Matrix (TPM) model, the magnitude of earthquake which caused tsunami is taken into account by considering each year separately. The earthquake magnitude is divided into a number of states. State 1 is tsunami potential and the other state is no tsunami potential. Tsunami states are divided as shown in Table 2.

State	Status
1	Tsunami occur
2	No tsunami occur

Table. 2. States of tsunami prediction system

The transition probabilities are estimated from

$$p_{ij(k)} = \frac{f_{ij}(k)}{C_i}$$

where $f_{ij}(k)$= historical frequency of transition from state i to state j within year k, and

C_i = total frequency of state i

Table 3, 4 and 5 show the sample history data of Indonesia which are gotten from National Oceanic and Atmospheric Administration [8].

5. CONCLUSION

A tsunami is an unstoppable natural hazard. They are probably most common in the Pacific Ocean but have occurred in the recent historical record in the Indian Ocean. They are very rare however in the Atlantic Ocean. The shape of the ocean floor alters the height of the tsunami by changing the ratio between the wavelength and the wave height of a tsunami. In general, the ratio of wavelength to wave height decreases as the wave travels into shallower water, causing the tsunami to grow in size.

To develop a system that copes with tsunami risk, this paper has proposed a method to estimate and predict tsunami in advance. In this paper, we have introduced a tsunami prediction and estimation system using Markov Chain method. We use the controlling factor in a Markov Chain called the transition probability. It is a conditional probability for the system to go to a particular new state, given the current state of the system. We can get fairly efficient estimates if we can determine the proper transition probabilities.

6. REFERENCES

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Year	Code	Country	Name	Latitude	Longitude
1907	1	INDONESIA	SW. SUMATRA	2	94.5
1908	1	INDONESIA	SW. SUMATRA	-5	100
1909	1	INDONESIA	SUMATRA	-2	101
1910	1	INDONESIA	SULAWESI	4	127
1913	1	INDONESIA	SULAWESI	4.5	126.5
1914	0	INDONESIA	BANDA SEA		
1914	1	INDONESIA	NW. IRIAN JAYA		
1917	0	INDONESIA	JAVA, INDONESIA		
1917	0	INDONESIA	BANDA SEA		
1918	6	INDONESIA	SULAWESI	3.1	125.5
1919	0	INDONESIA	NW. IRIAN JAYA		
. . .					
2000	1	INDONESIA	SULAWESI	-1.105	123.573
2002	1	INDONESIA	IRIAN JAYA	-1.757	134.297
2004	1	INDONESIA	SERAM ISLAND	-3.12	127.4
2004	1	INDONESIA	KEPULAUAN ALOR	-8.152	124.868
2005	1	INDONESIA	INDONESIA	2.085	97.108
2005	1	INDONESIA	KEPULAUAN MENTAWAI	-1.644	99.607
2006	1	INDONESIA	JAVA, INDONESIA	-9.254	107.411
2006	1	INDONESIA	SERAM ISLAND	-3.595	127.214
2007	1	INDONESIA	SUMATRA	-4.438	101.367

Table. 3. Sample Tsunami history data for Indonesia

Year	Name	Latitude	Longitude
1905	INDONESIA: MINAHASSA PENINSULA	1	123
1907	INDONESIA: NW SUMATRA: GUNUNGSITOLi, BARUS	2	94.5
1907	INDONESIA: TALAUD ISLANDS: KARAKELONG ISLAND	3	122
1907	INDONESIA: DJAILOLO GILOLO	1	127
1907	INDONESIA: SULAWESI: LEMO,COLO,ANJA,OLU CONGKO	-2	121
1908	INDONESIA: TIMOR	-10	129
1908	INDONESIA: CELEBES SEA	3	123
. . .			
2004	INDONESIA: TIMOR: KUPANG	-9.362	122.839
2004	INDONESIA: KEPULAUAN ALOR	-8.152	124.868
2004	INDONESIA: NABIRE	-3.609	135.404
2004	INDONESIA: SUMATRA: OFF WEST COAST	3.295	95.982

Table. 4. Sample Earthquake history data for Indonesia

Year	Code	Country	Name	Latitude	Longitude
1907	1	INDONESIA	SW. SUMATRA	2	94.5
1907	1	INDONESIA	KARAKELONG, TALAUD ISLANDS	3	122
1908	1	INDONESIA	SW. SUMATRA	-5	100
1909	1	INDONESIA	SUMATRA	-2	101
1910	1	INDONESIA	SULAWESI	4	127
1913	1	INDONESIA	SULAWESI	4.5	126.5
1914	1	INDONESIA	NW. IRIAN JAYA	-2	137
. . .					
1998	1	INDONESIA	TALIABU ISLAND, INDONESIA	-2.071	124.891
2000	1	INDONESIA	SULAWESI	-1.105	123.573
2002	1	INDONESIA	IRIAN JAYA	-1.757	134.297
2004	1	INDONESIA	SERAM ISLAND	-3.12	127.4
2004	1	INDONESIA	KEPULAUAN ALOR	-8.152	124.868
2004	1	INDONESIA	OFF W. COAST OF SUMATRA	3.295	95.982

Table. 5. Sample Tsunami history data caused by earthquake for Indonesia