SIMULATION OF HOT MUDFLOW DISASTER WITH CELL AUTOMATON AND VERIFICATION WITH SATELLITE IMAGERY DATA

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ABSTRACT:

Minimization differences on Cellular Automata approach to predict new inundated area of hot mudflow on LUSI mud eruption disaster which occurred in Sidoarjo area is proposed. There are three characteristics of hot mudflow that is unique such as surface material changes rapidly, surface temperature changes quickly and dike is constructed to avoid spill over. There are penetrations of hot mudflow through the dike and some landscape data on surrounding area of predicted cells. The proposed approach is powerful to simulate hot mudflow on this disaster.
Simulation results are compared to SPOT/HRV imagery data as well as ASTER/VNIR and ASTER derived digital elevation model and also compared to the actual measured data acquired from local government. It is found that the influence due to lattice size is clarified together with validation of simulation methods used.

1. INTRODUCTION

LUSI [1] mud eruption is unique mudflow disaster that has surface material changes rapidly, surface temperature changes quickly and dike is constructed to avoid spill over. LUSI produces vast quantity of hot and bubbling mud in the vicinity around 100,000- 170,000 m^3 per day [Rifai et al., 2007, Davis R., 2006, Tingay M., 2009]. The mud is very thick and viscous. The temperature of the mud in the centre area could easily exceed 90 degree centigrade [Rifai et al., 2007] and the temperature change quickly through the flow. The dike is constructed to avoid spill over because LUSI occurs in the urban area. Nowadays the mud height is above 17 meters and engulfing eight villages and displacing over 17,000 people [Tingay M., 2009]. Fig.1 shows some image and map of LUSI mud eruption. The top of the Fig.1 shows Google map of the LUSI mud erupted area while the middle shows aerial photo of the LUSI mud eruption. On the other hand, the bottom shows SPOT/HRV (Satellite Pour l'Observation de la Terre / High Resolution Visible) imagery data copyrighted by CRISP (Centre for Remote Imaging, Sensing and Processing).
One of important issue is how to predict location and direction of hot mudflow in the near future because this disaster occurs in the urban area. The people that stay on the surrounding area still want to know what happen in the future, and possibility that their home will inundated hot mudflow. Government built the dike and spillway to anticipate bigger impact that inundated villages, main road of East Java and railroad. It is easier when the direction and location of hot mudflow is known.
Cellular automata (CA) approach is a simple approach but powerful approach for disaster spreading such as flood, mudflow, and lava flow. CA approach is an alternative grid-based simulation framework allows both time-varying and geo-algebraic solution of spatial dynamics; this approach is simple and useful to simulate surface water flow [Parsons J.A. et al., 2007]. The CA model provides a first useful approximation for the computational treatment of fluid-dynamic phenomena [Argentini G., 2003]. CA model is a novel perspective in the modelling of surface flows in large plains, based on virtual landscapes created [Rinaldi P.R. et al., 2007]. The model is able to provide the evolution of the flow variables by some fluid dynamic phenomena such as tracking local water stocks, precipitation, infiltration, evapotranspiration, and intercellular flows [Rinaldi P.R. et al., 2007]. Some approaches based on empirically obtained equations are difficult to apply in general conditions, CA approach is an alternative approach for modelling complex phenomena such as lava flow [Vicari A. et al., 2006], [D'Ambrossio D. et al., 2003].
Based on Argentini, Vicari and D'Ambrossio, CA can be used to simulate hot mudflow that has some similar characteristics to lava flow and water flow. Combination of Argentini approach and Vicari approach has shown good approach to simulate hot mudflow, but it becomes difficult when we add some dynamical function on mass transport rules. D'Ambrossio approach is CA model with minimization difference that is simpler than previous approach and also show good result on lava flow, but it is not good enough for water flow. Combination of water flow and fluid flow using probability adjustment on minimization difference is proposed as a new approach of CA to simulate hot mudflow of LUSI mud eruption to predict the new inundated area on the future.

2. THEORETICAL BACKGROUND

2.1 Cellular Automata

Cellular Automata (CA) are discrete dynamical systems, widely utilized for modelling and simulating complex systems, whose evolution can be described in terms of local interactions [D'Ambrossio D. et al., 2003].

[1] **Lu**mpur **Si**doarjo; "lumpur" is the Indonesian word for mud). Retrieved from "http://en.wikipedia.org/wiki/Lusi"

Fig.1 LUSI mud eruption

The use of cellular automata for the representation of the evolution of a phenomenon, natural or not, presents two benefits respect a possible analytical description [Parsons J.A. et al., 2007]. Cellular automata (CA) are an artificial mathematical model of dynamical system. CA model consist of an array of cells, and each cell contain a limited range of values that is called cell's state. The cell's state is updated in discrete time step according to set of rules. These rules depend on the state of the cell or its neighbours in current time steps [Malamud B.D. et al., 2000]. According by definition, CA has three features. The first feature is state. State is a given variable for defining each cell. It can be shown in the numbers or properties. In a simplified expression, each cell is represented as sub landscape; therefore it is sum of individual location or type of growing area. There are many examples of state such as binary and non-binary state as shown in Fig.2.

The second feature is neighbours. Neighbours are some nearest cells from indicated cell. The neighbours size and position is called neighbourhood. Neighbourhood system depends on dimension of array of cells. There are many neighbourhood systems such as Von-Neumann Neighbourhood and Moore Neighbourhood on 2D CA as shown in Fig.3.

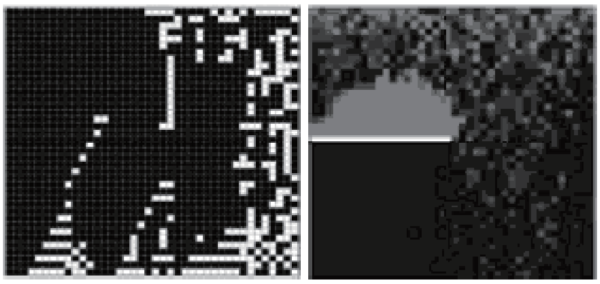
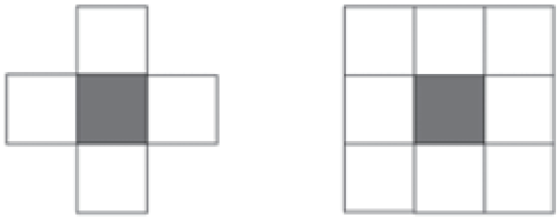


Fig.2 Binary and Non-binary state on 2D CA of fluid dynamics model



(a) Von-Neumann neighbourhood (b) Moore neighbourhood
Fig.3 Neighbourhood model on 2D CA

2.2 Minimization of Difference Approach

One of the CA approach to simulate viscous fluid is the minimization of difference approach. One alternative approach used to solve the complex fluid dynamic such as lava flow and hot mudflow without sophisticated mathematical formulation was introduced by Avolio M.V. et al., 2000. Another implementation of minimization difference approach used to simulate soil erosion by water is introduced by D'Ambrossio. This method obtain the lava flow spreading with many parameters such as viscosity and surface thermal changing that are similar with hot mudflow in our plan.
The minimization of difference approach has the following instruction to update states:

(a) A is the set of cell not eliminated. Its initial value is set to the number of its neighbours.
(b) The average height is found for the set of A of non-eliminated cells:

$$m = \frac{h_c + \sum_{i \in A} h_i}{n_A + 1}$$

where:
h_c is height of the centre cell.
h_i is height of the non-eliminated neighbour cells.
n_A is number of non-eliminated neighbour cells.
(c) The cells with height larger than average height are eliminated from A.
(d) Go to step (b) until no cell is to be eliminated.
(e) The flows, which minimize the height differences locally, are such that the new height of the non-

eliminated cell is the value of the average height.
For example of two-dimensional CA is shown in Fig.4.

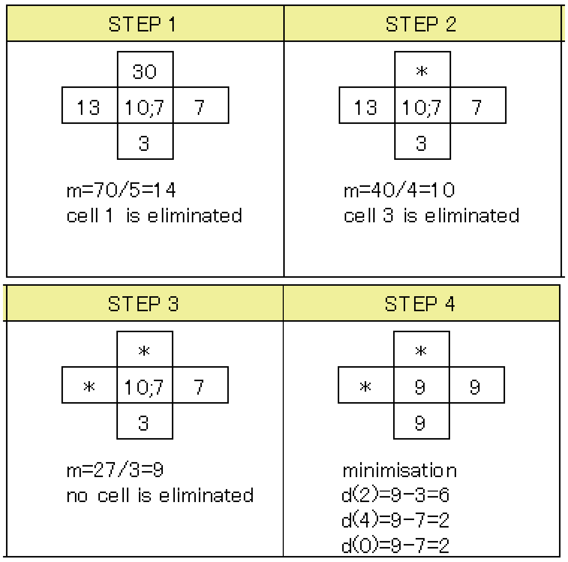


Fig.4 Example of minimization of differences in a two dimensional CA (2D CA).

3. PROPOSED METHOD

3.1 States Definition

The minimization method does not show the other situation around the cell and the mass transport creates direct equilibrium states as water or low viscous fluid. When the unknown variables add to the system, the characteristic of mass transport does not change. On the hot mudflow simulation we can not obtain all variables such as human built structures that have unknown characteristic, and we adjust the probability for moving factor and sedimentation factor.
We use three variables on each cell that are static soil, dynamic soil and mud. Static soil is the soil that can not change in the long time, and dynamic soil is the soil on the surface of soil that have possibility to change because erosion. The height of mud is written by s_{ij}, the height of dynamic soil is written by u_{ij}, and the height of static soil is written by g_{ij}. Probability of changing from dynamic soil to mud is p_m and it determines from differences of dynamic soil in the mud. Probability of changing from mud to soil is p_{vis} and it depends on viscosity. Fig.5 shows state variables on our simulation and some probability value for material changing caused by viscous flow.

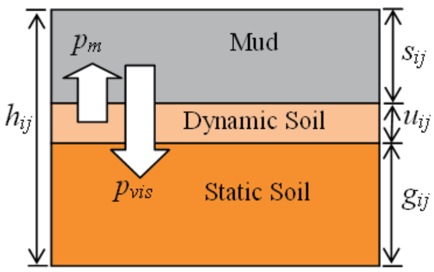


Fig.5 State definition

3.2 Proposed Rules

Our proposed approach based on minimization method has the following instruction to update states:

(a) A is the set of cell not eliminated. Its initial value is set to the number of its neighbours.

(b) The average height is found for the set of A of non-eliminated cells:

$$m = \frac{h_c + \sum_{i \in A} \left(h_i + p_m \cdot g_c\right)}{n_A + 1}$$

where:
h_c is height of the centre cell.
h_i is height of the non-eliminated neighbour cells.
n_A is number of non-eliminated neighbour cells.
p_m is probability of moving material.

(c) The cells with height larger than average height are eliminated from A.

(d) Go to step (b) until no cell is to be eliminated.

(e) The flows, which minimize the height differences locally, are such that the new height of the non-eliminated cell changes with difference of mass transport $\triangle h$.

$$\Delta h = m - (1 + p_{vis}).\min_{i \in A}(h_i)$$

where:
p_{vis} is probability of mixing material, how many water in the mud.

4. SIMULATION RESULTS

4.1 Model Specification

The simulation have purpose to know the inundated area for the future. For this purpose, we use some map data on February 2008 and August 2008 as shown in Fig.6. We use ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer Digital Elevation Model) and IKONOS (IKONOS is a high resolution satellite sensor owned and operated by GeoEye) data for landscape prediction. We will check the simulation result on one month step and compare it with the real data. The red area is mud and the height of mud is quantized and interpolated from ASTER DEM imagery data that has resolution 30m by 30m. The simulation start using map data on February 2008 as initial map, and predict mudflow inundated area on May 2008.
These image maps are base maps that need to quantize for our simulation. Every image data has image size approximate 3.705km by 4.036km. We use ASTER DEM to quantize the location/point that contains mud or not, and landscape map. When the resolution image is 400 by 400 pixels, pixel size is 9.2625m by 10.09m. This size is higher resolution than ASTER DEM that has resolution 30m by 30m. The other data, mud contains 70% water, high viscous and mud blows

around 150,000m^3 per day. We adjust volume of blowing, water percentage and two probabilities p_m and p_{vis} to simulate mudflow. Our simulation concern to know the location will inundate in the future.

Fig.6 Image maps on February 2008 (top), and August 2008 (bottom).

4.2 Comparison With Real Imagery Data

Fig.7 shows three maps; real map in May 2008 as target map, Simulation result map for May 2008, and comparison of real map and simulation result. Real mud areas is red colored area, simulation result mud area is blue colored area, and intersection of real map and simulation results area is pink colored area.

Fig.7 Real map on May 2008 (left), simulation result (middle) and overlay map (right)

In this result, intersection new predicted area about 67.78%, this value only for new area and initial area is not including to determine intersection area as shown in Fig.6.
Fig.8 shows intersection for new inundated area, and the percentage of intersection area is determined by percentage number of pixels of pink colored area on number of pixels of all new colored area. Cellular Automata approach using probabilistic adjustment on Minimization Differences obtains same location and direction with real data for short time prediction.

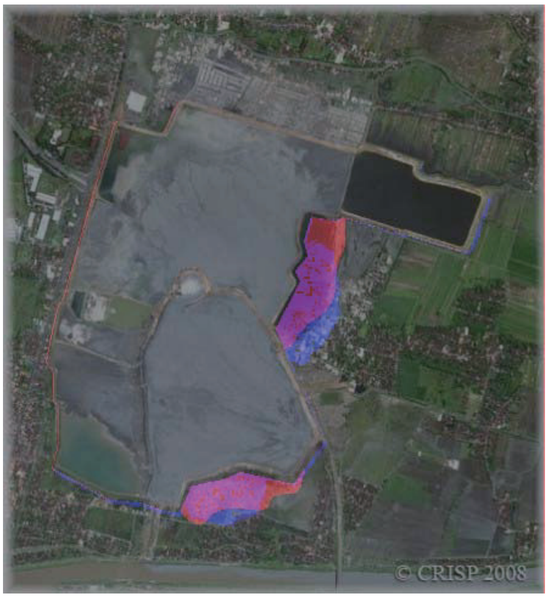


Fig.8 New inundated area and overlay between real data and simulation result

4.3 Lattice Size Effect

Lattice size analysis show how the simulation runs in some resolutions. We use lattice size ranges from 200 by 200 pixels as minimum resolution to 700 by 700 pixels as maximum resolution. Although the lattice size is infinitive in an ideal case, only a finite size of lattice is used for the computer simulation. Because CA approach is a microscopic approach to simulate hot mudflow disaster, this approach needs high resolution. It is reasonable that the prediction accuracy is saturated at the lattice size reaches at a large enough size. Therefore, the simulation with a variety of lattice size is conducted. Fig.9 shows prediction performance of the simulation (intersection area between simulation result and real data). As is shown in Fig.9, prediction performance is increased with increasing of resolution (lattice size). As the results, it could be said that the prediction performance would be saturated at around 80% of intersection area that is overlapped area between simulation result and actual area is approximately 80%.

CONCLUSION AND DISCUSSION

A new approach of cellular automata using probabilistic adjustment on minimization differences approach offers solution to predict new inundated area on hot mudflow disaster. This approach is easy to develop and has better performance than other previous approach to predict new inundated area that has same location and direction with real data. This approach as model-based approach depends on some parameters such as resolution; therefore this approach needs high resolution map to obtain a better result.
Also lattice size effect on prediction accuracy is confirmed. It is possible to eliminate the effect if we find a saturated prediction accuracy through simulations with a variety of lattice size.

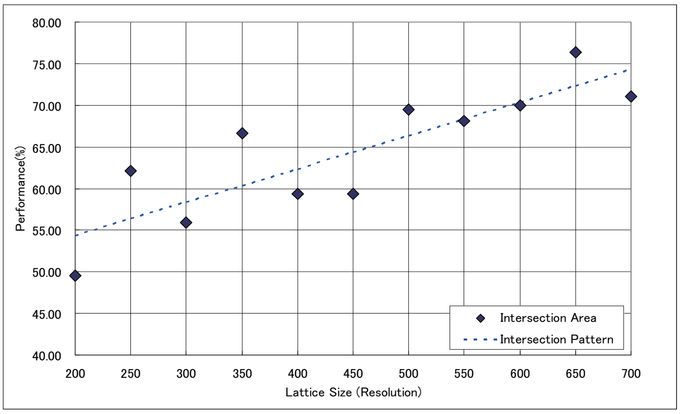


Fig.9 Performance of prediction versus lattice size.

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