SPATIAL MODELLING AND RISK ASSESMENT OF SIDOARJO MUD VOLCANIC FLOW

Rachman Rifai
February, 2008
SPATIAL MODELLING AND RISK ASSESSMENT OF SIDOARJO MUD VOLCANIC FLOW

by
Rachman Rifai

Thesis submitted to the Gadjah Mada University (Yogyakarta, Indonesia) and International Institute for Geo-information Science and Earth Observation (Enschede, The Netherlands) in partial fulfillment of the requirements for the degree of Master of Science in Geo-information for Spatial Planning and Risk Management, Specialisation: Natural Hazard Studies.

Supervisors:
Dr. Junun Sartohadi (First Supervisor - UGM)
Prof. Dr. V.G. (Victor) Jetten (Second Supervisor - ITC)
Dr. Dinand Alkema (Third Supervisor - ITC)

Thesis Assessment Board
Prof.Dr. Sutikno (Chair - UGM)
Dr. Junun Sartohadi (First Supervisor - UGM)
Prof.Dr. V.G. (Victor) Jetten (Second Supervisor - ITC)

Observer:
Drs. Tom Loran (Programme Director - ITC)

Advisor:
Dr. Th. W.J. van Asch (Utrecht University)
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I certify that although I may have conferred with others in preparing for this assignment, and drawn upon a range of sources cited in this work, the content of this thesis report is my original work.
Signed ...........
ABSTRACT

On 29 May 2006 mud volcano occurred in Sidoarjo-East Java 23 km south of Surabaya. This is a geological phenomenon due to over-pressurized sub-surface mud layers. This mud eruption appears to have been triggered by drilling of over-pressured porous and permeable limestone at a depth of – 2830 m below the surface (Davies, 2007). The discharge is very high with a rate of 7,000 – 115,000 m3/day, and has inundated 4 adjacent villages and so far 7000 people have displaced (UNDAC, July 2006).

In June 2006 the government built a dike around the centre of eruption to protect the surrounding environment from flood and inundation. Today more than 12 months after the start of the eruption, the mud volcano remains have high flow rates. This condition is very dangerous because if the dike breaks or the mud overtops, a wider area has high risk of being flooded by the mud.

To better understand which areas might be at risk or being flooded due to the mud, a prediction tool is needed to simulate the mud flow. Simulation of the inundation might be used for predicting what will happen in the future to know where inundation will take place in certain time to come. If one then knows what elements are at risk of being flooded, and if the vulnerability of the area is known a risk assessment can be done. Quantification of risk is needed as an input for preparation, evacuation, rehabilitation and reconstruction.

In this study, a 1D2D hydrodynamic model using SOBEK was implemented to create mud flow modeling. In the modelling approach five time scenarios of mud flow was generated represents five different condition of flowing of the mud. Four time scenarios were represented four times the dike break and one time scenario to represents the prediction of inundation without the dike. The scenarios have been implemented also used to test the behavior of mud flow compared with waterflood using SOBEK, since this software is designed to model waterflood.

The model result mostly give 40% agreement on the inundation extent. This result was achieved by comparing the inundation extent from the model with inundation extent from recorded event which was captured in the IKONOS image. The model also has output of inundation depth, but the result only give 10%, this probably because of land subsidence which was occurred in the study area. The land subsidence factor was ignored in this study because the magnitude and direction of land subsidence have spatial and temporal variations.

The impact assessment also be done in this study by analyzing the result of inundation extent and integrate with element at risk. The information of elements at risk was calculated from topographic map and IKONOS imagery.

Keyword : Mud volcano, Mud flow modeling, SOBEK, Hydrodynamic, DTM, Kriging, Interpolation.
ACKNOWLEDGEMENTS

First of all, I want to express my happiness by saying Alhamdulillah, praises to Allah for giving me the strength and opportunity to finish my MSc study in the best education environment at UGM and ITC.

I would like to thank to my office Bakosurtanal, especially to Ibu Dra. Titiek Suparwati as my superior and Dr. Poentodewo as the chief of Center of Topographical and Spatial Planning Mapping to support and give opportunity to continue my study. I would like also to thank to Bappenas and NESO to provide the scholarship and make this dream come true.

I would like to acknowledge my lovely wife Paramita, my beloved mother and parents in law with the enormous strength and courage bestowed on me to make this study a success. To my children Tomy and Indy who be my sources of inspiration and strength. To my late father who had given me the best education from elementary to tertiary education, may Allah give his soul mercy and forgiveness.

I deeply appreciate to my supervisors, Dr. Junun Sartohadi for gave me advices, suggestions and encourages. To Prof. Dr. V.G. Jetten who encourage me to conduct research on this topic and support me with valuable comments.

I appreciate with gratitude to Dr. Dinand Alkema as my third supervisor who patiently and tirelessly to guide me with valuable comments and suggestions during this research, especially during the writing of the thesis which is very short. I also feel very lucky because Dr. Alkema took a lot of effort to provide the necessary software and because of that this research finish successfully.

I would like to thank to Dr. van Asch who gave me enlightenment and share his knowledge during the discussion in the Utrecht University and via email. Those discussions have widened my knowledge of this topic.

I also would like to thank to Hoebnerk Cedric the student of University of Paris to share his valuable data during his fieldwork in Indonesia, without contribution of his data this research was impossible to succeed. To Dias who has helping me during the fieldwork and helped me to digitizing the maps.

I am grateful to all my friends in the double degree MSc program, Nugroho, Arif, Budi, Anna, Ebta, Estu, Maya, Mone, Defi, Muktaf, Safrudin, Rudy, Firda, Wulan, Utia, Dodi, Pak Hosen and Bu Lily, who have shared happiness during this study. And my pray to late Rhino who has passed away during this study, may Allah give mercy to his soul.
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CHAPTER 1. INTRODUCTION

1.1. Background

An eruption of steam, water and mud occurred in East Java on 29 May 2006 in Sidoarjo which is located at 23 km south of Surabaya, second largest city in Indonesia. This event, known as a mud volcanic flow is a geological phenomena due to overpressurized sub-surface mud layers usually associated with gas (Hensen et.al., 2006). The mud volcano occurred when mud and gas accumulated in sea sediments that were trapped in subduction zones where one tectonic plate slides under another. Mud volcanoes have burst on every continent, but are abundant in the south Caspian region (offshore and onshore Azerbaijan) and offshore Indonesia in the East Java basin (Noorden, 2006). The Sidoarjo mud volcano seems to be a hybrid between a typical mud volcano and hydrothermal vents with mud temperatures as high as 60 to 70 centigrade and very high concentrations of hydrogen sulphide gas. This indicates that hydrothermal activity is going on at the same time (Noorden, 2006). This mud eruption appears to have been triggered by drilling of overpressured porous and permeable limestone at a depth of – 2830 m below the surface (Davies, 2007). The discharge is very high with a rate of 7,000 – 115,000 m3/day), and has inundated 4 adjacent villages and so far 7000 people have displaced (UNDAC, July 2006).

The hot mud flow is located near urban areas with a dense population and it has direct and indirect impacts to the surrounding area. The direct impact is that people have lost their houses or lost their jobs because the factory where they used to work sank by mud, or were displaced from their own neighborhood. The indirect impact of this hazard is the reduction economic activity in the whole province because Sidoarjo is located along the main transportation line between Surabaya, the capital city of the province and the cities inside the province.

In June 2006 the government built a dike around the centre of eruption to protect the surrounding environment from flood and inundation. Today more than 12 months after the start of the eruption, the mud volcano remains have high flow rates. This condition is very dangerous because if the dike breaks or the mud overtops the dike, a wider area has high risk of being flooded by the mud.

1.2. Problem Statement

It is very difficult to predict if and when the mud volcanic flow will stop or whether it can be stopped at all. Many techniques have been tried to stop the eruption of mud volcano but until this moment nothing was successful. The mud volcano keeps flowing. To better understand which areas might be at risk or being flooded due by the mud, a prediction tool is needed to simulate the mudflow. Simulation of the inundation might be used for predicting what will happen in the future to know where inundation will takes place in certain time to come. If one then knows what elements are at risk of being flooded, and if the vulnerability of the area is known a risk assessment can be
done. Quantification of risk is needed as an input for preparation, evacuation, rehabilitation and reconstruction.

Many scientists have conducted research in the field of mud flow or debris flow modeling. Many modeling approaches were developed and had their advantages and disadvantages. The decision to choose what type of the model should be used depends on the condition of the area, the quality of available data. In country like Indonesia the availability of data and the software is a major limitation to apply most of these models.

1.3. Research Objectives

The main objectives of this research are:

a. To reconstruct the mud flow in a dynamic spatial modeling environment.
b. To predict the propagation of the mud flows, to estimate the area that might be affected in present and future.
c. To calibrate and validate the model based on comparison with the actual event.
d. To assess mud flow hazard which affected elements at risk such as settlements, buildings, roads, factory etc.

1.4. Research Question

a. What types of data are needed to build a DEM as a basis for the mud flow modeling?
b. How far the inundation of mud flows in the next 5, 10 and 20 years?
c. How reliable and accurate the model?
d. How many properties and infrastructure will be affected by mud flow?

1.5. Limitation of the study

The study area poses several restrictions to the research:

a. The area surrounding is dangerous due to toxic gas (H₂S), new unpredicted bubbles (explosion of mud volcano), and high temperatures of the mud (70 – 130 centigrade). This means we cannot move or observe everywhere in the study area freely, there are some place that we cannot enter due to that situation.
b. There were some human activities to control the mud flow, therefore the behavior of mud flow was not completely natural. This condition will influence to the comparison data.
c. High potential in social conflict, we have to take care to make interview with people surrounding.
1.6. Structure of the Thesis

This thesis contains 8 chapters.

The first chapter contains the introduction of the research, research background, research problems, research objectives and research questions.

Chapter two contains a detailed description of the study area, the climate condition, the topography, the relief and the geology.

Chapter three covers the literature review of other research related to this research.

Chapter four describes the methodology of the research, and the expected result.

Chapter five describes how DTM generated, integrate with the dike and the quality assessment of the DTM.

Chapter six contains a detailed explanation of mud flow modeling using SOBEK software, model calibration, model validation and sensitivity analysis of the model.

Chapter seven describes the impact assessment of mud flow to the elements at risk.

Chapter eight, this chapter contains conclusion and recommendations.
CHAPTER 2. LANDSCAPE CHARACTERISTICS OF THE STUDY AREA

2.1. Geographical Characteristics

Located 23 km from Surabaya, Sidoarjo lies from 112.5° and 112.9° east longitude to 7.3° and 7.5° degrees south latitude. The Sidoarjo City is the Capital of the regency, situated in the lowland of the Brantas watershed, located between two river branches, Kali Porong and Kali Surabaya, therefore Sidoarjo is deltaic of Brantas watershed, and the people of this area called the city is ‘Kota Delta’ or Deltaic City. The regency is bordered on the north by Surabaya municipality and Gresik regency, on the south by Pasuruan regency, on the west by Mojokerto regency and on the east by the straits of Madura. ([http://www.petra.ac.id/eastjava/cities/sidoarjo/sidoarjo.htm accessed 20 June 2007](http://www.petra.ac.id/eastjava/cities/sidoarjo/sidoarjo.htm accessed 20 June 2007))

The climate condition of Sidoarjo is similar to another regions in East Java, it has a wet tropical climate, with an average annual rainfall of 1900 mm and a annual temperature range of 21 to 34°C.

2.2. Topography

East Java Province can be divided into 3 physiographic zone: the southern zone is a plateau, the central zone is a volcanic area and northern zone is a folded area. Sidoarjo is located in the northern area. In this mountainous area there are 3 volcanoes, which are called Anjasmoro group, and comprise of Mt. Arjuno (3,239 m), Mt. Welirang
(3.156 meter) and Mt. Anjasmor (2.277 meter). These three volcanoes are still active and some scientists relate the mud volcano to this volcanic activity. Nearby these mountains there is a small hill named Mt.Watukosek and by interpreting the landsat image there is indication that this hill was a result of fault and if we make a line far away to the north this fault will meet with mud volcano vent.

This study area is located in the lowland which has elevation range of 0 to 5 m. This area is deltaic of Brantas watershed, so mostly the relief is flat and nearby to the coastal, the distance to the sea is 15 km.

2.3. Geology

Geologically, Sidoarjo is located in the East Java Basin at the south east margin of the Sunda platform where Mesozoic basic rock and mélange rock are found (IAGI, 2006). The East Java basin is an inverted extensional basin (Matthews and Bransden, 1995, in Davis et al., 2007). Beneath this part of Java there is a series of half graben that have a strike in east-west direction, and are filled with marine muds and carbonates. The Java Basin has been geologically active since the Paleogene epoch. The Basin started to become overpressurized during the Oligo_Miocene period (Osborne and Swarbrick, 1997 in Davies, 2007). Some of the overpressurized sediments came up to become mud volcanoes, which have been observed at Sangiran Dome and Bleduk kuwu near Purwodadi 200 km from Sidoarjo.
The mud that is released near Sidoarjo is, according to Matthews and Bransden, 1995 (Davis 2007) Overpressured lower Miocene clays which probably equivalent to the Tuban or Tawun Formations (similar age to the Kujung limestone) and the Upper Kalibeng Formation. Also Watanabe and Kadar, (1985, in Davies, 2007) considered this Formation to be the source of the mud.

2.3.1. Stratigraphy

As described by Suyoto (2006) the stratigraphical sequence in Sidoarjo, based on the age of formation from old to young can be seen below:
1. Ngimbang Formation
The lowest formation (the oldest), consist layers of sandstone, debris and siltstones, formerly located in a shallow sea environment as demonstrated by the dominant content of foraminifera. The age of formation was early Oligocene and the dominant lithology is limestone.

2. Kujung Formation
This formation was deposited during the late Oligocene and similar with Ngimbang formation, this formation was deposited in a sea environment with depths between 200 – 500 m. This is indicated by the abundant benthos. The formation is characterized by napol and claystones but on the upper part there is limestone and reef deposit. The biota content consists also of foraminifera and seaweed.

3. Prupuh Formation
The Prupuh formation lies from Panceng heading to the east, through Paciran – Palang – Tuban then continuous to the south. The age of this formation is the late Oligocene up to the lower Miocene. The formation is characterized by dirty white-colored limestone and light grayish white colored bio-clastic limestone.

4. Kalibeng Formation
The Kalibeng formation thickness varies between 500 – 700 m and is revealed in the Kalibeng river, Jombang. The formation age is the late Miocene up to middle part of Pliocene, which at the upper part consist of interspersions of tuffan, tuff, lapili tuff and breccia sandstone.

5. Lidah Formation
The Lidah formation has two layers, the upper part was sedimentoed in a shallow sea environment with a depth of 20 – 50 m and the bottom part was sedimentoed in the protected marine environment at the depth of 200 – 300 m. The formation estimated has age between Pliocene up to Pleistocene.

6. Pucangan Formation
The Pucangan formation is located in central west of Kendeng zone spread out to Eastern part of Kendeng zone, and it is revealed in Mt. Pucangan, Jombang. The formation consists of tuff napalan and contains mollusca, insertions of breccia, tuffan sandstone and conglomerate of sandstone. The age of this formation is Pliocene to late Pliocene.

7. Kabuh Formation
The Kabuh formation is found in Sumberangin sub district, Jombang. This formation is famous among archaeologists because many fossil of vertebrate were found, Eugene Dubois found the skull of Homoerectus at Sangiran and von Konigswald found vertebrate fossils at Trinil (Suyoto, 2006). The thickness of the formation is varies from 100 m to 700 m, and have age of Mid Pleistocene.

8. Notopuro Formation
The formation as its name was revealed at Notopuro a small village at Madiun, and has age estimated in the late Pleistocene. The thickness of the formation is
about 240 m and consists of tuff interspersed with tuffan sandstone, volcanic breccia and conglomerate.

2.3.2. Structural Geology

There are several Main structures which dominated in the northern part of the East Java Basin (Guntoro, 2006), These are:

- A Structural pattern on the NNE-SSW that is well expressed in Java sea and controlled by the faulting of the basic rock.

- West – East patterns that are well expressed on the West-East fault series (strike slip fault), and folds with West-East pattern are known as Kendeng fold.

In the surroundings of the mud volcano in Porong – Sidoarjo, can be identified there are lineament heading to SW – NE spread out and continue to the Madura island which is separate the two folded systems. The central vent of mud volcano in the study area is located 200 m SW of Banjarpanji-1 well (Kadar et.al, 2006), bordered in the north by Kendeng zone - gentle hilly area and in the south by a series of quaternary volcanoes. In the geological map of East Java can be identified a surface structure known as Watukosek fault, this fault is nearly located in same line with Mud volcano in Sidoarjo (Porong MV), the similarity of the pattern and direction between the fault and mud volcano were interpreted as there are any relationship between mud volcano and the fault zone (Guntoro, 2006., Kadar, et.al, 2006). There are another several mud volcanoes which are lies in the same line with Porong MV; Pulungan MV, Gunung Anyar MV and Bujeltasek in Madura island (Kadar, et.al, 2006).

![Fig 2-8. The distribution of mud volcano in Central and East Java](image1)

![Fig 2-9. Mud volcano in Sidoarjo, East Java](image2)
2.4. Land use

The landuse information of study area was extracted from the 1996 Topographical map (RBI) with scale of 1:10,000 that updated using an Ikonos image from 2002 and through field checking. Mainly the land use of Porong sub-district are characterized by high density urban settlement, industrial estates and agricultural land. The types of agricultural lands are paddy field, orchard (sugar cane and tobacco) and mix garden which mostly located in sub urban area.

Physical infrastructure can also found to support industrial area surrounding such as toll way, bridge, factory building, railway etc. The area of Porong sub district is one of Sidoarjo regency area which intend to be built become the largest industrial area in East Java.
2.5. Land subsidence

Land subsidence is a secondary hazard cause by the mud volcano in Sidoarjo. This phenomena can be see visually on the infrastructure such as the bridge in the toll road that become fractured and cracked because of displacement of the foundation, now the toll road is abandoned.

The cause of land subsidence is mainly because of the weight of mud volcano have been spew, until October 2006 there was 6.15 million cubics meter volume of mud volcano on the ground (inside the dike) and because of tectonic movement of Watukosek fault in the area (Media center lusi, October 2006, 3rd edition).

The survey conducted by Bandung Institute of Technology (ITB) conclude there were land displacement in the horizontal and vertical direction which has spatial and temporal variations in magnitude and direction (Abidin et al, 2006). According to Abidin et.al, the vertical displacement probably cause by ground relaxation due to mud flows, mud loading, land settlement and geological structure. The result of Survey on the June – October 2006 can be seen below:
Fig 2-15. Subsidence in x (horizontal) direction.  

Fig 2-16. Subsidence in y (vertical) direction.  

Fig 2-17. Subsidence measurement bar graph (Abidin, et al., 2006)
CHAPTER 3. LITERATURE REVIEW

3. 1. Mud volcano and Diapirism

The term mud volcano was coined by Stewart & Davis (2006) and refers to a geological structure with a constructional edifice and some kind of feeder that connect the volcano to its source (Davis et al, 2007). A mud volcano either on the earth surface or on the bottom of the ocean is probably the result of a pressurized mud diapir called a piercement structure, and is often associated with gas and oil deposits in subduction zones. Mud volcanoes are also often associated with lava volcanoes. They often release hydrocarbon gases, such as methane, but sometimes also other gases helium. (www.wikipedia.org accessed 19 june 2007)

To explain the triggering mechanism and evolution of mud volcanism and mud diapirism a good understanding of the tectonic history is needed (Soto et al, 2003. They are found in various tectonic settings, but most have been reported in accretional wedges, with compressional tectonic forces, such as in Barbados (Martin & Kestner, 1996 in Soto et al., 2003), Makran (Wiedicke et al., 2001, in Soto et al., 2003), Eastern Indonesia (Barber et al., 1986, in Soto et al., 2003).

3. 2. The origin and cause of Mud Volcano in Sidoarjo

There are many discussion related to the cause of the mud volcano in Sidoarjo. A group of scientists and experts in geology and geophysics have different opinion about what was the cause of the mud, but there are 4 major hypotheses as resume by Guntoro, 2006 :

- Due to drilling activity :
  This became the dominant opinion in the public. It is true that the first eruption of mud volcano is only 200 m from the drilling activity of a gas exploration, and that the mud volcano was erupted just shortly after a failure of drilling process. In the drilling report the drilling problem occurred when they reached 9200 feet in the Kujung formation (Guntoro, 2006).
- Due to Yogyakarta earthquake
  The Yogyakarta earthquake happened 2 days before the mud volcano, at a
distance of 200 km from the mud volcano. The existing of fault line
surrounding area could be key factor because the energy from earthquake
was released along the fault plane rocks and this resulted in a number of
deformation processes (Guntoro, 2006) and may have caused a liquefaction in
the Kalibeng formation at a depth of approximately 2000 ft – 6000 ft which is
overpressured (Guntoro, 2006).

- Due to mud volcano activity
  The activity of mud volcano is generally indicated by seepage of gas, oil or
salt water. This is very common in East Java especially around Sidoarjo.
There were also found the existence of methane gas which is one indication
of mud volcano activity. Observed data also indicate the existence of
methane gas associated with mud flow in this area (Guntoro, 2006). Guntoro
also conclude that the occurrence of mud flows in the study area were
probably because of natural phenomenon due to mud volcano activity.

- Due to the presence of Geothermal activity
  The existence of heat associated with mud volcano lead to this hypothesis. So
there is a surface reservoir which is continuously recharging the geothermal
source. Geologically in the south of mud volcano vent there is volcanic
complex area, and probably this is the source of active magma (Guntoro,
2006).

The first hypothesis was also proposed by Davies, et.al., 2006. In the figure 3-3, a
schematic three dimensional representation of developmental stages of the mud volcano
in Sidoarjo. The sequence of mud volcano eruption process after Davies et.al, are as
follows:

A. In march to may 2006 drilling activity (Banjarpanji-1 well) was drilled to
Kujung formation through Kalibeng formation which consisted of
overpressured mud.
B. May 2006, Kujung Formation (carbonates) were penetrated and caused a
‘kick’ (influx of fluid into well bore), this caused hydrofracturing of the
overlying strata (probably within the Kalibeng Formation. Mud entered the
wellbore and through permeable strata and fracture systems caused of
entrainment of overpressured mud.
C. May to December 2006, entrainment of Kalibeng Formation caused a
subterranean conduit to form, the walls of which undergo collapse.
D. Post 2006, caldera forms around the vent, and gentle sag-like subsidence of
the region.
3.3. Flow Classification

The National Research Council Committee on methodologies for predicting mud flows (NRC, 1982) was initiated to delineate between hyperconcentrated sediment flows and mass wasting (Flo-2D manual). There is a broad range between flowing water and sediment from clear water to landslides and there is continuum in the physics for them. The committee proposed four categories: water floods, mud flood, mud flows and landslides.

Flowing material is considered to be Newtonian or non-Newtonian based on linear or non-linear function when shear stress acting to it. The relationship between each function is described by figure 3-4. as follows:

![Figure 3-4. Shear stress as a function of Shear rate of fluid deformation](Flo-2D manual)
Hyper-concentrated flow that occur worldwide is in the range of 20 to 55 percent concentration by volume (Flo-2D manual). Mud Flood events are defined as hyperconcentrated flows with more than 20 % of sediment concentration, and defined as water flood if less than 20 %.

Mud flood may be difficult to distinguish from water floods but the fluid properties of mud floods are very different with much higher density and viscosity than water floods (Flo-2D manual). Mud flow is non Newtonian, very viscous, non homogeneous and transient flood and the characteristics of its fluid properties are significantly different. Its flow behavior is a function of fluid matrix properties, roughness, slope and channel geometry, the fine sediment - silt and clay are controls the flow properties including yield stress, density and viscosity (Flo-2D manual). The behavior of hyperconcentrated sediment as a function of sediment concentration could be seen at Table below:

Table 3- 1. Flow classification based on concentration, Flo-2D manual handbook.

<table>
<thead>
<tr>
<th>Sediment Concentration</th>
<th>Flow Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>by Volume</td>
<td>by Weight</td>
</tr>
<tr>
<td>Landslide</td>
<td>0.65 - 0.80</td>
</tr>
<tr>
<td></td>
<td>0.55 - 0.65</td>
</tr>
<tr>
<td>Mudflow</td>
<td>0.48 - 0.55</td>
</tr>
<tr>
<td></td>
<td>0.45 - 0.48</td>
</tr>
<tr>
<td>Mud Flood</td>
<td>0.40 - 0.45</td>
</tr>
<tr>
<td></td>
<td>0.35 - 0.40</td>
</tr>
<tr>
<td></td>
<td>0.30 - 0.35</td>
</tr>
<tr>
<td></td>
<td>0.20 - 0.30</td>
</tr>
<tr>
<td>Water Flood</td>
<td>&lt; 0.20</td>
</tr>
</tbody>
</table>
The Figure 3-5. clearly explain about the relationship between sediment concentration by volume, flow classification and the fluid type.

3.4. Rheological characteristics of mud flow

Rheology is the study of the deformation and flow of matter under the influence of an applied stress. The term was coined by Eugene Bingham, a professor at Lehigh University, in 1920, the term was inspired by Heraclitus’s famous expression ‘panta rei’ or ‘everything flows’. (www.wikipedia.org)

Rheology concept is applied when the classical theory of fluid mechanic or the concept of elasticity and Newtonian fluids mechanics of material cannot explain or describe the mechanical behavior of fluid material. The diagram below shows the different states of material and the relation with rheological characteristics:
Different type of rheological characteristics will influence the type of flows which will be applied (Newtonian, viscous, granular etc). Other important factor to consider in the selection of the appropriate models are the approximation and numerical method employed (Arattano, et.al). This is also important factor in the different type of rheological characteristics of moving material to simulate kinematic mud and debris flow over complex terrain (Santiago et al., 2007). This model is based on 2D finite difference solution of a depth averaged form of the equation of motion for a flow continuum. Another numerical model also applied but mostly in 1D model (Hungr, 1995; Arattano and Franzi, 2003, Naef et al., 2006., in Santiago et al., 2007).

There are several rheological parameters which are frequently used to model the flow material like viscosity, shear stress, yield strength, cohesive strength. Other parameters to be selected depend on the type of material to model.

Mostly the discussion of rheological material deal with debris flow, because a real debris flow may show characteristics of a viscous flow, muddy or turbulent type flow or granular flow and this flow regimes could be different event in the same channel (Arattano and Franzi, 2004 in Naef, et.al, 2006). Material properties change within the wave and the limits between these flows regimes are difficult to determine in the field (Naef, et.al, 2006).

Differences of rheological characteristics within flow regimes are reflected in the flow resistance relations (Naef, et.al, 2006) and may be broadly divided into:

- one phase models, either slurry of water and fine material or the entire fluid-solid mixture (Naef, et.al, 2006)
- two phase models, both fluid and solid phase (Bozhinsky and Nazarov, 2006; Iverson and Denlinger, 2001, in Naef, et.al, 2006)
- hybrid models, different layers with different flow resistance characteristics (Takahashi, 2000., in Naef, et.al, 2006)
Spatial Modelling and Risk Assessment of Sidoarjo Mud Volcanic Flow

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Flow resistance relation</th>
<th>Flow resistance term $S_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Full Bingham</td>
<td>$S_f = \frac{\tau_0}{\rho g h}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tau_0$ can be determined by: $2 \tau_0^2 - 3 \left( \tau_y + 2 \eta_B \mu_B \right) \tau_0^3 + \tau_y = 0$</td>
</tr>
<tr>
<td>B</td>
<td>Simplified Bingham</td>
<td>$S_f = \frac{\tau_0}{\rho g h}$ with $\tau_0 = 1.5 \tau_y + 3 \frac{\eta_B}{\mu_B}$</td>
</tr>
<tr>
<td>C</td>
<td>Voellmy</td>
<td>$S_f = \frac{n_B \sqrt{\tau^2}}{g \eta B} + \cos \alpha \tan \delta$</td>
</tr>
<tr>
<td>D</td>
<td>Turbulent &amp; Coulomb</td>
<td>$S_f = \frac{n_B \sqrt{\tau^2}}{g \eta B} + \cos \alpha \tan \delta$</td>
</tr>
<tr>
<td>E</td>
<td>Turbulent &amp; Yield</td>
<td>$S_f = \frac{n_B \sqrt{\tau^2}}{g \eta B} + \frac{\tau_y}{\mu_B}$</td>
</tr>
<tr>
<td>F</td>
<td>Turbulent, Coulomb &amp; yield</td>
<td>$S_f = \frac{n_B \sqrt{\tau^2}}{g \eta B} + \frac{\tau_y}{\mu_B}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with $\tau_y = \min(\tau_y: \mu_B \rho g \cos \alpha \tan \delta)$</td>
</tr>
<tr>
<td>G</td>
<td>Quadratic</td>
<td>$S_f = \frac{n_B \sqrt{\tau^2}}{g \eta B} + \frac{\tau_y}{\mu_B}$</td>
</tr>
<tr>
<td>H</td>
<td>Coulomb viscous</td>
<td>Full Bingham with $\tau_y = \mu_B \rho g \cos \alpha \tan \delta$</td>
</tr>
</tbody>
</table>

Table 3-2. Flow resistance term, Naef, et.al, 2006.

The conceptual model of mud flows (Johnson and Rodine, 1984; Costa, 1984; in Naef, et.al, 2006) and stony debris flow (Takahashi, 1991; in Naef, et.al, 2006) describe the flow with proportion of fine material where the coarser particles dominate the flow behavior (Naef, et.al, 2006).

Mud flows have two different behaviors, in laminar flow the regime is described as a Bingham fluid, but in non-laminar flow its behavior explained by the Coulomb–viscous relation (Johnson and Rodine, 1984; in Naef, et.al, 2006):

$$\tau = \tau_y + \mu_B \left( \frac{du}{dz} \right) = \tau_c + \sigma \tan \phi + \mu_B \left( \frac{du}{dz} \right)$$

Where:

$\tau$  = shear stress
$\tau_y$ = yield stress
$\tau_c$ = cohesive stress
$\sigma$ = solid density
$\phi$  = friction angle of the solid material
$\mu_B$  = Bingham viscosity
$$\left( \frac{du}{dz} \right)$$  = shear rate
3.5. Mud flow modeling

Mud flow or debris flow is a form of hyperconcentrated sediment flow similar to floods, lahars or landslides. Such events may become a disaster when they occur in the dense human settlements such as in urban areas. Scientists try to understand the behavior and characteristics of these phenomena numerical modeling.

Many methods have been applied to simulate mud flow or debris flow, for example cellular automata model have been used to simulate lava flow based on a Monte Carlo approach, the model using MAGFLOW was applied to reproduce a lava flow formed during the 2001 Etna eruption (Vicari et al., 2006), similar model were also applied using the latest developments of the cellular Automata model SCIDDICA for simulating debris flow phenomena, this model was applied to simulate of the 1992 Tessina (Italy) earth flow, the 1984 Mt. Ontake (Japan) debris avalanche and debris flow that occurred in 1998 at Sarno (Italy) (D’ Ambrossio et al., 2003).

Another method to simulate material flow is presented by Murton and Biggs, (2002) who applied a numerical model of mud volcanoes and their flows in the gulf of Cadiz. A model of isostatic compensation between the mud column and the sediment overlying the mud source was used to predict the depth to the mud reservoir beneath mud volcanoes. Once erupted, the general behavior of an individual mud flow could be described and predicted using a viscous gravity-current model. The model shows that conical-shaped mud volcanoes comprise multiple, superimposed radial flows in which the thickness, eruption rate and speed of individual mud flows strongly depends on the viscosity, density and overpressure of the erupted mud. Using these parameters, the model predicts the lowermost flows will be the oldest, thickest and have the greatest length of run-out while the uppermost flows will be the youngest, thinnest and shortest. Mikos et al., (2006) applied numerical simulation of debris flows triggered from thestrug rock fall source area in west Slovenia. They used two mathematical models, one dimensional model DEBRIF-1D and two dimensional model FLO-2D, using this model Mikos et al, were prepared a hazard map for the village for possible new debris flow.

Martini, et al., 2004 uses a 2D-1D hydrodynamic model to study of flood waves and suspended sediment transport in Brenta river, Veneto – Italy. The 2D-1D hydrodynamic model is integration of two dimensional depth integrated momentum and continuity equation which are modified to take into account the bottom irregularities. This model merged 2D computational domain and 1D network which is consist small channel and the regulation devices like weirs, sluices, banks, pipes, water pumps etc. The coupled of 2D-1D scheme is use to describe the effects of small channel in the model and has been applied successfully with an accurate resolution flow field in the study area.
3.6. SOBEK Software

There are many software to model the flow material either in 1D or 2D flood modeling. Flood modeling in 1 dimensional software is used to model the flow in the channel system, information on water depth and flow velocity can be calculated at each cross section of the channel. But the 1D flood modeling has limitation because water flow assumed parallel to the main direction of the channel. An example of 1D software is HEC-RAS developed by the US Army Corps of Engineer and MIKE 11 by the Danish Hydraulic Institute (DHI).

A 2 dimensional flood modeling is used to model overland flow of water. This requires an input about terrain topography such as DTM or DSM. The 2D flood model can provide information about inundation extent, the flow velocity and the flood depth. The 2D software for example are FLS, LISFLOOD, Telemac 2D, MIKE_21 and SOBEK (Rahman, 2006). The 2D software are more popular because the capability to simulate flood water similar to real condition.

The SOBEK software has been developed by WL|Delft Hydraulics in partnership with the National Dutch Institute of Inland Water Management and Wastewater Treatment (RIZA), and this software is the concrete result of experience from many institutions in Netherlands (SOBEK hlp). This software is combination of 1D and 2D flood model, therefore SOBEK can integrate both channel flow modeling and overland modeling. The 2D flood model in SOBEK has been designed to model overland flow on the initially dry system and in complex topography (Alkema et.al, 2004 in Rahman, 2006).

SOBEK as 2D flood model requires DTM as an input of elevation data. This software is designed to interface with another GIS format provided by other software. SOBEK is based on high performance computer technology that means the software can handle water networks of any size, big or small. The network is determined by DTM as network platform and reaches, cross sections and structures. The amount of these parameters influenced the complexity and the time of computation.

The DTM resolution has to determine first to achieve the optimum result. This decision is based on the application to create, for example in large scale of urban flood modeling requires detail pixel size and high vertical accuracy, therefore the coverage area have to reduced to maintain the time computation in reasonable values.

SOBEK was designated with advanced graphic display capability so it is possible to superimpose the model result over a map or imagery of the area. This software also have capability to animate the result of flooding and this application will make analysis of flooding easier.
CHAPTER 4. METHODOLOGY

This research mainly focuses on mud flows modeling using spatial dynamic environment and risk assessment for surrounding area. Modeling will be done using SOBEK to simulate the flow of mud and its inundation, while risk assessment will use remote sensing. Remote sensing technique use to obtain the elements at risk of being affected by the mud, such as houses, roads, factories, buildings etc. The conceptual framework of this methodology can be seen in Figure 4-5.

4.1. Research phase

To elaborate the main objectives this research are divided into 7 phase, which describe as follows:

4.1.1. Preparation and data acquisition

a. Literature study
This step will be the longest activity in the research process started from beginning to the end, literature study will be carried out in order to develop knowledge and research concepts. This part will mostly deal with mud flows and anything related to mud flows such as debris flow or sediment flow, the software, Risk and Hazard and dynamic modeling. Including in the literature study was the discussion and consultation with scientists who have experience and knowledge in this study, such consultation was done with Dr. Th. W.J. van Asch from Faculty of Geoscience, Utrecht University who has a long experience in study landslide and mud flow.

b. Determination of the model accuracy.
Model accuracy depends on the terrain or elevation data will be used. In this research Digital Terrain Model will be created from the topographic map of 1:10.000 scale, which have contour interval of 5 meters. Accuracy of the model will be based on this DTM.

c. Data collecting.
Data collecting can be divided into two types based on the data type, first type is data for modeling and second type is data for calculating element at risk. Data for modeling is topographic map with scale of 1:10.000 with contour interval of 5 meters, this data used as input of DTM. The topographic map in the scale of 1:10.000 was the best scale available in that area.
Second type of data is satellite imagery, there were multi temporal satellite imagery, satellite before disaster happen used to calculate the number of element at risk which affected by mudflow. Ikonos imagery with acquisition year of 2002 use to calculate houses, roads, building etc, while Landsat ETM used to delineate land use in the surrounding area.
Ancillary data also collected during this stage, for example characteristic of mud flow such as discharge, density and viscosity.

d. Field work preparation
During this stage preparation of field work will be take place, that will include what type of data will be collected, design route and location of
points observation, preparation of field equipment such as wireless GPS, PDA, laptop, camera, accommodation in the field and obtaining research permits from local government.

4.1.2. Data Processing and Modeling

In this research modeling of mud flow was based on original terrain or topography, because the condition of this area were not naturally anymore, government have built the dike to protect area surrounding. Potential mud flow inundation was created based on original DEM and this scenario is useful to simulate and predict how far the inundation will be in certain period of time.

The DTM combined with dike or embankment represented actual changes of topography in surrounding area, this new DTM (actual DTM) used to calibrate and validate the reliability of the model, from this result we know how high the reliability of the model.

This stage consists a set of practical work describes below:

a. Generated original DTM.

This map represents the terrain before mud volcanic erupted. It is derived from topographic maps. This DTM will be used to simulate the potential inundation of mud flow for 1, 5, 10 or 20 next years. The grid-based DTM was generated from topographic maps at a scale 1:10.000 using krigging interpolation. The grid size was 10 meters to maintain its relief detail and accuracy.

b. Generated actual DTM

This map represents the relief changes on the study area. Man made elevation such as dike has been built in the surrounding area to prevent the spreading of inundation.

The reconstruction of dike was created based on several sources, Ikonos imagery from CRISP website (www.crisp.nus.edu) which are downloadable for free and have a 6 m resolution. This data was used to assess the dike width after geometrically corrected and digitized, while the report maps which is made by government agency is data for the dike height.

c. Constructed Mud Flow Modeling s A potential mud flow inundation.

This modeling will simulate the inundation of mud flow without dike or embankment.

d. Constructing of Mud Flow Modeling type B (actual mud flow inundation).

This modeling simulate the recent of mud flow, and will use in validation and calibration process.

4.1.3. Fieldwork

This stage comprises the fieldwork activities and consists a set of practical work below:

a. Observing the development of mud flow in several observation point samples.
b. Collecting data of actual inundation area from government authority (spatial and tabular).

c. Observing elements at risk which are affected by inundation of mud flow such as land use, houses, buildings, roads, railway, river etc.

d. Collecting mud samples in several point observation, then it will be analyzed at laboratory to measure density, viscosity and concentration of mud and water (either by weight or by volume).

Fig 4-1. The pictures shows several sample point location

4.1.4. Post Fieldwork

The fieldwork was conducted two times, the first was preliminary fieldwork and it was accompanied by two supervisors Drs. Michiel Damen and Dr. Junun Sartohadi. This fieldwork had purpose as follows:

- observed the study area in general,
- observed how far the inundation area
- checked element at risk which affected by the hazard
- checked the fault in the field

The second fieldwork was conducted to collect samples of mud volcano, and then analyzed the samples to measure viscosity, density and concentration of water in the mud. The result of the laboratory test can be shown below:
Table 4-1. Laboratory test result of mud volcano rheology

<table>
<thead>
<tr>
<th>No. Sample</th>
<th>Viscosity (Poise)</th>
<th>Density (g/cm³)</th>
<th>Water content (% weight)</th>
<th>Temperature (Celsius)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>1.3929</td>
<td>60.9306</td>
<td>60.6</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>1.3661</td>
<td>62.4943</td>
<td>52.3</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>1.3987</td>
<td>60.8612</td>
<td>51.3</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>1.4042</td>
<td>59.3063</td>
<td>38.1</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
<td>1.4176</td>
<td>59.0002</td>
<td>33.8</td>
</tr>
</tbody>
</table>

During this stage the secondary data to be analyzed and grouped into 5 category:
- Imagery, pictures and photographs
- Hardcopy Map: monthly inundation maps and height of inundation maps
- Digital Map: topography, land use
- Video recorded of the hazard
- Literatures and papers

4.1.5. Calibration and validation

Calibration is to determine the set of parameters and their values to get the best results from the model and validation is to determine whether the model have a good accuracy or not, this stage can be divided into a set of practical work:
a. Create several scenarios model with different parameters input. In this study input parameter is surface roughness. Surface roughness is derived from land use map and gives the manning coefficient to every land use types. Several manning coefficient maps is created to be input to the model. The result model then to be compared with recorded event and determined which one of the manning coefficient is more similar to the recorded event.

b. Digitizing reliable source maps (inundation maps) from secondary data such as report maps.

c. Calculating the accuracy and reliability of the model.
Calculate the reliability of the model by comparing the condition of the model with actual event. Parameter to be compared is the area of inundation and the depth of the mud.
The area of inundation and the depth of the model can easily measured direct on the model result, this two parameters then to be compared with actual event by measure recorded data or map. Recorded data can be found on the monitoring map from government authority for inundation events in the past, but recent event cannot be measured by direct measurement due to high temperature of surface mud and we do not have properly equipments to do the kind of work.

d. Evaluating the model.
Evaluation of the model was to determine the advantages and limitations of the model.

4.1.6. Risk Assessment

This stage of the research is to predict the consequences of the mud in the future. The following steps have been taken:

a. Identifying, and delineating the area of mud inundation into several zones which have a certain level of vulnerability based on flow modeling.
b. Interpreting satellite imagery to collect the information about land use, number of houses, settlements and infrastructure which could be affected. Interpretation of satellite imagery used to updated existing topographic map which produced by Bakosurtanal. There are two type topographic map which is used in this research, first is topographic map scale of 1:25,000, used to calculate land use affected by this hazard, and second is topographic map scale of 1:10,000 used to quantified elements at risk such as number of houses, buildings and roads. Topographic map scale 1:10,000 is large scale map so single building is easy to be identified and to be calculated, this is become an input when quantifying elements at risk.

c. To estimate the consequences for the elements that might be exposed to the mud, the potential damage is estimated base on the number of elements at risk within the inundation coverage.

4.1.7. Reporting/thesis writing

In this stage the whole research process start with introduction and end at conclusion and recommendation was wrote down, and become the final step of the thesis. Reporting also has function as a tool to communicate the result of the research to other scientists and also to the public. The documentation about the whole research, the data, pictures and maps have documented both in printed paper and in digital format stored in the CD.

4.2. Materials

4.2.1. Data requirement

In order to make good modeling of mud volcanic flow it is necessary to provide data as main material in good quality, the data requirement to create the modeling are as follows:
- Data of elevation of the study area.
Elevation is primary data have to be provided, generally elevation is found on contour map or DEM, but we have to determined first on what level of accuracy the contour map or DEM is needed. To create flow modeling the more accuracy of the elevation data (vertical accuracy) is the better. Another factor have to take account is elevation data have to have capability to represent all objects on the surface such as building, road, trees, dike etc. This type of elevation data can be provided by LIDAR or INSAR, both type of data have capability to represents all object on the surface, but off course very costly, and country like Indonesia do not have such kind of data.

- Data of man made structure (dike)
  Dike or dam usually built in area which has high risk due to flood and inundation. This kind of feature must be drawn or constructed on the elevation data, this feature can be reconstructed on the map from secondary data such as technical drawing. But in hazard area like in the study area, an emergency work is first priority than ‘well planned’ work, so the dike was built first than planning process, therefore very difficult to find such kind of technical drawing. The reconstruction of dike in this research was done by using data from the regularly report or by interviewing government officer in the field and also from Ikonos imagery.

- Data of high resolution satellite, before and after
  High resolution satellite was very useful to calculate element at risk in the study area both before and after the hazard, but availability of the data was become a problem due to cost of the data.

- Data of medium resolution satellite, before and after
  Medium resolution satellite data was used to calculate and analyze the impact of the hazard on the land use over larger area, and very useful to predict land use affected in the next 5 or 10 years.

- Data of structure geology, medium scale
  Geological map scale of 1:100.000 used to get overview of geological setting especially structural aspect such as fault or lineament.

- Recorded events until recent (height and distribution of the inundation)
  Calibration and validation process are need data of past events. Recorded data of past even provide information such as the spread of mud flow and the height of inundation.

- Rheology of mud volcano : viscosity, density, friction, yield stress, concentration of water and mud.
  This data can be found on the secondary data if the laboratory test has been conducted or the laboratory test conducted during the research. There is not easy to find the laboratory which has capability to test all parameters, for instance in Indonesia we could not find such laboratory during the time of research, only parameters of viscosity, density and concentration of water and mud could be tested.
- Sample of mud from point observation well distributed from central vent to spillway.
To make good quality of the model which simulated the real event similarly, the data of mud rheology from every point in the field which well distributed is necessary but unfortunately the condition in the field is different due to high dangerous hazard area, for instance in the near central vent the temperature is reach 100 degrees centigrade and event more and has high concentration of sulphur in the air. Due to that condition people was prohibited to enter inside 500 m radius from central vent unless have sufficient safety equipment.

4.2.2. Data collected
During the fieldwork and post fieldwork the data necessary for this research have been collected from various sources, there are three type source of data, from government offices, from private organization and from laboratory work. The type data have been collected can be seen in the table below:

Table 4-2. Type of research data

<table>
<thead>
<tr>
<th>No</th>
<th>Type of data and map</th>
<th>Specification</th>
<th>Sources</th>
<th>Status</th>
<th>Aim/Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Topographic Map 1:10.000</td>
<td>Digital Format</td>
<td>Bakosurtanal</td>
<td>Ready</td>
<td>DTM, Base Map, Element at risk</td>
</tr>
<tr>
<td>2</td>
<td>Topographic Map 1:25.000</td>
<td>Digital Format</td>
<td>Bakosurtanal</td>
<td>Ready</td>
<td>Land cover, Manning coefficient</td>
</tr>
<tr>
<td>3</td>
<td>IKONOS image, 2002</td>
<td>Digital Format</td>
<td>Bakosurtanal</td>
<td>Ready</td>
<td>Land Cover or Land Use before disaster, Large scale - detail</td>
</tr>
<tr>
<td>4</td>
<td>Aster Image, 2006</td>
<td>Digital Format</td>
<td>Bakosurtanal</td>
<td>Ready</td>
<td>Land Cover or Land Use after disaster, Medium scale</td>
</tr>
<tr>
<td>5</td>
<td>Geological Map</td>
<td>Scanned</td>
<td>Dinas ESDM Jatim</td>
<td>Ready</td>
<td>Geological setting</td>
</tr>
<tr>
<td>6</td>
<td>Land Use map</td>
<td>Digital Format</td>
<td>Updated – Ikonos imagery</td>
<td>Ready</td>
<td>Elements at risk</td>
</tr>
<tr>
<td>7</td>
<td>Element at Risk map</td>
<td>Digital Format</td>
<td>Updated – Ikonos imagery</td>
<td>Ready</td>
<td>Elements at risk</td>
</tr>
<tr>
<td>8</td>
<td>Rheology of Mud</td>
<td>Tabular</td>
<td>Laboratory test</td>
<td>Ready</td>
<td>Modeling input parameter</td>
</tr>
<tr>
<td>9</td>
<td>Geological Map</td>
<td>Scanned</td>
<td>Dinas ESDM Jatim</td>
<td>Ready</td>
<td>Geological setting</td>
</tr>
</tbody>
</table>

4.3. Software
The software necessary for this research are SOBEK, Ilwis and Arc GIS. SOBEK is to be used to create the model, Ilwis is used to process satellite imagery and support SOBEK program, ArcGIS is used to process vector data.
4.4. Flow chart

Fig 4-5. Schematic diagram of research work flow.

4.5. Expected Result

Expected outcomes of the research are:

a. A dynamic simulation of the mud flow in the study area
b. Evaluation about the reliability of the model
c. Inundation map of mud flow
d. Element at Risk Map
e. An assessment of the mud volcanic flow in the study area
f. Thesis report
CHAPTER 5. DTM GENERATION

5.1. Elevation Data

Elevation data can be represented in various ways such as a contour line, spot height or Digital Elevation Model. Mostly elevation data is represented in the form of Digital Elevation Model that as stated by Maune, (2001 in Rahman, 2006), is the digital form of the terrain or elevation data to be used, manipulated or analyzed displayed directly by computer in 3D.

The DEM or Digital Elevation Model is a 3D representation of elevation values, such as topographical elevation, groundwater table, a geological layer, etc. It is a general term and it includes the terms DTM and DSM.

The DTM or Digital Terrain Model is a 3D representation of the natural terrain or ground surface.

The DSM or Digital Surface Model is a 3D representation of the natural and non-natural terrain, it thus includes man-made objects like embankments, dikes, buildings, etc.

The DEM and DTM application are as follows (www.wikipedia.com):

- Geometric correction or rectification of aerial photography and satellite imagery
- Modeling water flow or mass movement (floods or landslide)
- 3D visualization
- Relief map and physical models
- Terrain reduction of gravimetry measurement
- Extracting terrain parameters
- Terrain analyses (physical geography, geology, geomorphology)

The important factor of using DEM or DTM is how accurate elevation at every pixel (absolute accuracy) and how accurately the morphology is represented (relative accuracy). The absolute and relative accuracy are depending on several factors (Hengl, T et.al, 2003):

- Terrain roughness
- Pixel size or grid spacing
- Vertical resolution
- Sampling density (elevation data collection method)
- Interpolation algorithm
- Terrain analysis algorithm
Digital Elevation/Terrain model is available through several types of acquisition data:

a. Land surveying

Land surveying or known as surveying is the technique and science to measure the position of an object on the earth surface in three dimensions, and usually used to establish land maps and boundaries for ownership (www.wikipedia.org). This technique has been developed since the beginning of recorded history or about 5000 years ago, the application of surveying is widespread for example construction, transportation, building and mapping.

In mapping, surveying is used to acquire the elevation data for creating a DTM. Elevation data obtained from this technique is the most accurate with accuracy ranges between centimeters to millimeters. But since the operation of this technique is relies on a human operator, it’s time consuming and only covering a small area, even when use the automatic DGPS. Thus the disadvantage of this technique is that it is cost and time consuming. For the detail application over a small area such as engineering this technique is the best choice.

b. Photogrammetry (aerial photo and satellite imagery)

Photogrammetry is science of measuring the earth surface and geometric object properties which are determined from photographic images. Historically this technique was developed since mid-nineteenth century. Through this technique three dimensional coordinates of point an object determined by measurements from at least two photographic images taken from different positions (www.wikipedia.com).

Remote sensing techniques, either from airborne (aerial photo) or space borne (satellite imagery), have been used to provide elevation data. DTM generation from remotely sensed imagery has been raised since many satellite remote sensing have been launched and operational, there are SPOT-5, ASTER, EOS-1, CartoSat and ORBVIEW. The use of this satellite imagery because provide an excellent source with low cost and fairly accurate resolution and coverage a large area, although this technique cannot penetrate cloud cover and depends on weather condition. The accuracy of this technique ranging from sub meter (aerial photo) to several meter (satellite imagery) (Hutchinson, 1999 in Tennakoon, 2004). The DTM from aerial photographs with sub meter accuracy is provide good data for flood modelling but DTM from satellite imagery has not sufficient accuracy for detailed urban application (Tennakoon, 2004).

![Image](www.geoeye.com)

*Fig 5-2. The diagram showing satellite system derived elevation data*
Photogrammetry technique is commonly used in earth science such as topographic mapping, terrain analysis, geomorphology and geology. Nowadays this technique also used in many other fields such as architecture, engineering, manufacture, archaeologists and so on.

c. Radar Satellite (Radarsat)

Stereo radar or Synthetic Aperture Radar is a radargrammetry technique similar to photogrammetry. Photogrammetry is based on optical sensors or passive systems, while radargrammetry is based on a radar sensor or active systems. The active system like radar based sensor emits its own signal from satellite and records the signal return reflected by object on the ground surface. The passive systems like optical based sensor has the energy from other sources such as light from the sun. Therefore the advantages of Radar data is that it penetrates through cloud cover and it can acquire data both day and night. Radarsat uses two passes of a radar satellite to generate a digital elevation map which has resolution about ten meters.

The important parameter in Radar is Doppler Centroid which is the basic principle of the DEM generation from radar image. The Doppler centroid gives the look angle and the slant range which has distance from sensor to object on the ground. These parameters together with orbit model make possible to derive three dimensional vector position of object measured. By implementing geodetic equations, this position can be transformed into map coordinates (www.radarsat.com).

d. Radar airborne (Insar/Ifsar)

Terrain mapping from airborne radar is using interferometry technique called Interferometry synthetic aperture radar. Interferometry as measurement technique was developed by Michelson and Morley in 1879 (Tennant, 2000), and since then Interferometry has been used in scientific investigation from space astronomy to differential GPS techniques. For surface terrain observances Interferometry SAR was applied to the planet Venus but the first experiment to measure terrain elevation of the earth was reported by Graham in 1974, and after that it took 10 more years before it was used extensively for non military application. Various groups and research agencies are developed this technique including the US Jet Propulsion Laboratory (JPL), the Canadian Centre for Remote Sensing (CCRS), the Environmental Institute of Michigan, Sandia Laboratories and others (Tenant, 2000).

e. Lidar

LIDAR stands for Light Detection and Ranging and it is the technology to measure earth surface elevation using pulses of laser light striking the surfaces of the Earth and measuring the time of pulse return. The laser scanner and sensor are mounted in the bottom of an airplane (similar with aerial camera) with an IMU – inertial measuring unit and GPS (www.satimagingcorp.com). The recorded data will be used to measure the time between the emission of a pulse by the laser and its return back to the sensor to calculate the distance to the terrain surface. This mapping process requires
ground base location survey or GCP measurement similar with other photogrammetric mapping. But different with surveys which use any optical sensor, lidar mapping can be done day or night.

![Lidar system, www.satimagingcorp.com](image)

The Lidar systems also have capability to acquire data of intensity reflectance, the value of reflectance of each surface features will be different and this called as lidar intensity. This intensity can be further processed to produced a geo referenced raster file and similar with conventional image and very useful to identification of land cover on the surface.

5.2. Data Source

The elevation data was derived from topographic map scale 1:10.000 produced by Bakosurtanal, an Indonesian Government Agency for surveying and mapping. The topographic map was produced in 1999 using interferometry synthetic aperture radar data acquired in 1997, and updated using aerial photograph scale 1:30.000 for urban area and field survey carried out in 1999. This mapping was a part of National spatial planning mapping project in 6 Provinces.

The area that were covered in this project were ‘Puncak’ Bogor and the area surrounding Surabaya city including Sidoarjo. The spatial resolution of this image was 2.5 m horizontal and 1.25 m vertical.

![The contour map of the study area](image)
5.3. Digital Terrain Model for Flow Modeling

DTM can be generated using various source of data such as direct survey, optical based elevation data, radar or Lidar. The use of the type of elevation data is depend on the application which intend to create, for flood modeling highly accurate and recent topographic data should be used, but this is not always ready due to budget and time constraint (Sanders, 2007). Primarily in flood modeling DTM are used to parameterize an algorithm of 2D hydrodynamic simulation and compared with observed condition on the field or with flood report and published flood maps (Sanders, 2007).

Highly accurate DTM is required for flood modeling in urban areas because many detail of infrastructure and building such as road elevation, curb and obstacle can be captured. Such structural elements are playing important role in controlling the behavior of water flow (Rahman, 2006). Building as solid blocks will make overestimation on flood extent and depth, but treated building as rough surface could make underestimation of flood extent and depth (Rahman, 2006). The urban area which have 10 percent or more of built up area will have significant effect in flood extent (El-Ashmawy 2003, in Rahman, 2006).

DTM resolution is determined based on the terrain or landscape. In low relief the impacts of the resolution is less but in high relief the impact is significant (Anderson et.al in Rahman, 2006). Therefore the determination of DTM accuracy for flood modeling is depends on the relief of study area. Terrain characteristics also have important role in the determination of elevation data type, for example in the relatively flat terrain SRTM has better vertical accuracy compared with high terrain, and interferometry SAR with 1 m vertical accuracy for flood modeling purposes need further processing especially in rough terrain and vegetated areas (Sanders, 2007).

Sanders 2007, showed that DEMs which based on airborne LIDAR has the best result for flood modeling application because LIDAR has high vertical accuracy (0.1 m) and the ability to separate bare earth, built up area and vegetation, while DEM based on airborne Ifsar need further processing because of suffer from noise and speckle although have high resolution (1 m).

Table 5-1. Optimum pixel size to various model applications (Tennakoon, 2004).

<table>
<thead>
<tr>
<th>Application</th>
<th>DTM Res. 5m</th>
<th>DTM Res. 7.5m</th>
<th>DTM Res. 10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood hazard mapping in urban areas</td>
<td></td>
<td></td>
<td>Adequate</td>
</tr>
<tr>
<td>Detailed studies related to velocity measurments, sedimentation and erosion</td>
<td></td>
<td>Adequate</td>
<td></td>
</tr>
<tr>
<td>Studies (EIA) relating to individual structures or reclamation of small lands</td>
<td>Adequate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small scale EIA studies in regional level for investigating effects on new road/small scale reclamation projects.</td>
<td></td>
<td>Adequate</td>
<td></td>
</tr>
</tbody>
</table>
5.4. DTM Interpolation Method

Generally the elevation data at every location is not readily available. For example, the height of the terrain has to be measured before it can be used, the completeness of the data over entire area is the best condition but it is usually difficult or expensive. The required data can be collect by measurement at sample location and then various interpolation method can be employed to fill the gaps at unsampled location (Demirham, 2003). The choice of interpolation method depends on the condition of the terrain and landscape of the surrounding area. Surface interpolation of the terrain create a continuous or prediction surface from sampled point values, this is the basic principle of DEM generation.

Interpolation methods also known as Spatial Interpolation are based on the principle that closer locations will have more similar elevation than those far apart (Demirhan, 2003). The differences in elevation values from point to point are related to their distance, and in the interpolation algorithms the points which have the closest location will have the biggest influence (Rahman, 2006). Although different interpolation methods are based on this common principle, the DEM resulted from each method will have different characteristics and accuracies (Leberl, 1973 in Kidner 2003).

The DEM interpolation method can be classified into two types: smoothing effect and proximity effect. The smoothing effect is divided into two groups exact and approximate. Also proximity can be divided into two groups; global and local (Shresta, 2003). An exact interpolator preserves the value of the source data in the output map, an approximate interpolator estimates all values of the output map on the value of several surrounding points. There are many of the interpolation methods that have been developed, nearest neighbor, moving average, triangular irregular network with linier interpolation, inverse distance weighting, krigging and many more.

The different interpolation approaches should be implemented for different terrain characteristics because there is no the best method which is clearly superior and appropriate to all surface and landscape condition (Maune, 2001, Shresta, 2003). However the quality of DEM depends on how smoothness and tension can be described and stream and ridges can be incorporated (Mitkas and Mitasova in Shresta 2003). Therefore every terrain characteristics have to be determined with different parameter value. The flat terrain will need different parameter with hilly or mountainous terrain.

5.4.1. TIN (Triangulated Irregular Network with Linear Interpolation)

Triangular Irregular Networks or TIN have been widely used by the GIS community as digital means of representing surface morphology. A TIN is a set of digital geographic data which constructed by non over-lapping triangles computed from irregularly spaced points that have x, y and z values. TINs are based on triangular element or facets with vertices at the sample points (Moore, et.al, 1991 in Wilson and Gallant, 2000), and usually using Delauney triangulation (Weibel and Heller, 2001). The TINs edges form contiguous, non-overlapping triangular facets and can be used to capture the linier features that have important role such as fault, ridge and stream courses (Moore, et.al 1991 in Wilson and Gallant, 2000).
The DEM generated using TIN interpolation can represent sudden changes in relief and that is very important in the morphotectonic investigation, therefore TIN has advantages in morphotectonic analysis (McCullagh, 1988 in Jordan, 2007). TINs are also very efficient in representing area with uniform slopes therefore very useful for identification of tectonically induced erosion morphology of spurs and pediment (Riley and Moore, 1993 in Jordan 2007). TINs are usually used for high precision modeling in small areas, such as in engineering application because they allow calculation of planimetric area, surface and volume. But TINs have disadvantages since this method requires a large amount of high accuracy data which are expensive and probably not available (Maune, 2001, in Rahman, 2006)

![Triangulated Irregular Network - TIN](image)

**5.4.2. Minimum Curvature**

The minimum curvature interpolation is widely used in the earth sciences, it has been proposed by Briggs (1974) for automatic contouring of geophysical data (Demirhan, 2003). It is not an exact interpolator, minimum curvature generates the smoothest possible terrain while attempting to honour the data as close as possible and replaces the observation value by the interpolated value in the same location. The minimum curvature interpolation generates a surface similar to a thin linearly elastic plate passing through each of the input points with a minimum amount of bending. It generates the smooth surface by repeatedly applying an equation over the grid until either the maximum number of iterations is reached or the values are less than the maximum residual.

Demirhan, 2003 showed the equation of minimum curvature is as follows,

for \(d=2\) – two dimensional cubic spline, the curvature is obtained in term of observation point values \(f(x_i,y_j), \ i=1 \ldots I; \ j=1 \ldots J\)

where I and J are the number of grids in the x and y direction

\(h\) is regular grid spacing of observation.
The total squared curvature:

\[ C = \sum_i \sum_j C(x_i, y_j)^2 \]

where,

\[ C(x_i, y_j) = \left| f(x_i, y_{j+1}) + f(x_i, y_{j-1}) + f(x_{i+1}, y_j) + f(x_{i-1}, y_j) - 4f(x_i, y_j) \right| / h^2 \]

\( f(.) \) denotes the observed value if its argument, \( x \) and \( y \) coincide with location of observed data.

There are several parameters that have to be determined when using minimum curvature interpolation method as described in Surfer help:

- **Internal and Boundary Tension**
  This parameter used to control the number of this bowing on the interior, the higher the less the bowing, for example a higher value of tension makes areas in the observation look like facets of gemstone. The values of internal tension and boundary tension are ranging from 0 to 1.

- **Relaxation factor**
  The algorithm of minimum curvature is using a successive over-relaxation algorithm to solve the specified partial differential equation. The interior is updated using chessboard strategy as discussed in Press, et.al (1988), the higher values of relaxation factor the faster algorithms run the lower will cause the algorithm run slower, the values to be determined by trial and error.

- **Convergence**
  Convergence factor is similar with maximum residual.

### 5.4.3. Kriging

Kriging is originated by Krige in 1951 and developed by Matheron (1971) is an advanced geostatistical procedure that generates an estimated surface from a scattered set of points with z-values (Demirham, 2003). This interpolation method is a complex procedure that requires knowledge about spatial statistics before using this method. Kriging is based on the regionalized variable theory that assumes, the spatial variation in the data represented by z values is statistically homogenous in the entire surface and the distance between every sample points reflects a spatial correlation and can be used to describe the variation in the surface (arcgis hlp). In this method the multisteps process have to be done:

- exploratory statistical analysis of the data
- variogram modeling
- creating the surface

The spatial variation is quantified using semivariogram which is estimated by the sample variogram through computation of the input point dataset. The variogram is
a function to analysed and expressed the spatial variability and estimated by the following equation:

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} (Z(xi) - Z(xi + h))^2$$

Where

- $\gamma(h)$ = semi variance at distance h
- $n$ is the number of observation separated by a distance $h$
- $Z(x)$ = elevation value at position $i$
- $Z(xi + h)$ = elevation value at $h$ distance from $i$

The semivariogram depicts the spatial autocorrelation of the measured sample point, measured points which has close to each other will have a smaller difference squared than those farther apart, the basic principle in geography. In krigging we have to determine range, sill and nugget to describe the model.
5.4.4. IDW – Inverse Distance Weighted

The inverse distance weighted interpolation method or also known as Inverse distance to a power is weighted average interpolator and it can be an exact or smoothing interpolator. The basic principle in inverse distance weighted is the points that are located close to one another are more alike than the points that location farther. In this interpolation data are weighted during the process and this will make the influence of one point to another decline with distance from grid node. The weighting value will control how the weighting factors drop off when distance to a grid node is increase. (ArcGis Help).

Inverse distance weighted interpolation used the following equation:

\[
\hat{Z}_j = \frac{\sum_{i=1}^{n} \frac{Z_i}{h_{ij}^\beta}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^\beta}}
\]

\[
h_{ij} = \sqrt{d_{ij}^2 + \delta^2}
\]

Where:
- \(h_{ij}\) is the effective separation distance between grid node \(j\) and the neighboring point \(i\)
- \(\hat{Z}_j\) is the interpolated value for grid node \(j\)
- \(Z_i\) are the neighboring points
- \(d_{ij}\) is the distance between the grid node \(j\) and the neighboring point \(i\)
- \(\beta\) is the weighting power
- \(\delta\) is the smoothing parameter

5.5. Topography Map Accuracy assessment

5.5.1. Horizontal Accuracy

Horizontal accuracy standard of USNMAS or US National Map Accuracy Standard which were published in 1947 was the guideline of horizontal accuracy topographic map and because at that time the computer has not been widely used as today, the accuracy standard was for paper map. It was stated that for maps which has scale larger than 1:20.000 has to had 10 percent of the points tested more than 1/30 inch, and for maps in scale of 1:20.000 or smaller 1/50 inch, both in publication scale.
For digital maps there are a new guideline has been published called NSSDA – National Standard for Spatial Data Accuracy. In this guideline, the horizontal accuracy for topographic map can be describe below,

\[
RMSE_x = \sqrt{\frac{3(x_{\text{data},i} - x_{\text{check},i})^2}{n}}
\]

\[
RMSE_y = \sqrt{\frac{3(y_{\text{data},i} - y_{\text{check},i})^2}{n}}
\]

where:
- \(x_{\text{data},i}, y_{\text{data},i}\) are check point coordinates of the \(i\) th in the dataset
- \(x_{\text{check},i}, y_{\text{check},i}\) are check point coordinates of the \(i\) th in the independent source of higher accuracy
- \(n\) is the total number of check point
- \(i\) is an integer ranging from 1 to \(n\)

Horizontal RMSE is:

\[
RMSE_r = \sqrt{\frac{3((x_{\text{data},i} - x_{\text{check},i})^2 + (y_{\text{data},i} - y_{\text{check},i})^2)}{n}}
\]

\[
= \sqrt{RMSE_x^2 + RMSE_y^2}
\]

When RMSE\(_x\) = RMSE\(_y\)

If \(RMSE_x = RMSE_y\)

\[
RMSE_r = \sqrt{(2 \times RMSE_x^2)} = \sqrt{(2 \times RMSE_y^2)}
\]

\[
= 1.4142 \times RMSE_x = 1.4142 \times RMSE_y
\]

Based on assumption that the systematic error is eliminated, that the error is normally distributed and independent in each \(x\) and \(y\) direction. The factor of 2.4477 is used to calculate horizontal accuracy at the level of 95% confidence (Greenwalt and Schultz, 1968). The horizontal accuracy (NSSDA) is computed using the formula:

\[
Accuracy_r = 2.477 \times RMSE_x = 2.477 \times RMSE_y
\]

\[
= 2.477 \times RMSE_r \div 1.4142
\]

\[
Accuracy_r = 1.7308 \times RMSE_r
\]

When RMSE \(\min/\max\) is in the range of 0.6 and 1.0, circular standard error at confidence level of 39.5% may be approximated as \(0.5 \times (\text{RMSE}_x + \text{RMSE}_y)\) (Greenwalt and Schultz, 1968). The horizontal accuracy value should be based on formula:

\[
Accuracy_r \sim 2.4477 \times 0.5 \times (RMSE_x + RMSE_y)
\]
Table 5.2. Horizontal accuracy of topographical map in several standards (Maune, 2001 in Rahman, 2006)

<table>
<thead>
<tr>
<th>Map scale (NMAS)</th>
<th>NMAS – CMAS 90% confidence level (m)</th>
<th>RMSE (NSSDA) (m)</th>
<th>NSSDA Accuracy 95% confidence level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1,200</td>
<td>1.006</td>
<td>0.671</td>
<td>1.158</td>
</tr>
<tr>
<td>1:2,400</td>
<td>2.042</td>
<td>1.341</td>
<td>2.316</td>
</tr>
<tr>
<td>1:4,800</td>
<td>4.054</td>
<td>2.682</td>
<td>4.633</td>
</tr>
<tr>
<td>1:6,000</td>
<td>5.090</td>
<td>3.353</td>
<td>5.791</td>
</tr>
<tr>
<td>1:12,000</td>
<td>10.150</td>
<td>6.706</td>
<td>11.582</td>
</tr>
<tr>
<td>1:24,000</td>
<td>12.192</td>
<td>8.016</td>
<td>13.899</td>
</tr>
</tbody>
</table>

Table 5.3. ASPRS Accuracy Standards for large scale maps.

<table>
<thead>
<tr>
<th>Map scale</th>
<th>Class 1 Planimetric accuracy Limiting RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:50</td>
<td>0.0125</td>
</tr>
<tr>
<td>1:100</td>
<td>0.025</td>
</tr>
<tr>
<td>1:200</td>
<td>0.050</td>
</tr>
<tr>
<td>1:500</td>
<td>0.125</td>
</tr>
<tr>
<td>1:1,000</td>
<td>0.25</td>
</tr>
<tr>
<td>1:2,000</td>
<td>0.5</td>
</tr>
<tr>
<td>1:4,000</td>
<td>1.0</td>
</tr>
<tr>
<td>1:5,000</td>
<td>1.25</td>
</tr>
<tr>
<td>1:10,000</td>
<td>2.5</td>
</tr>
<tr>
<td>1:20,000</td>
<td>5.0</td>
</tr>
</tbody>
</table>

5.5.2. Vertical Accuracy

NMAS guideline stated that vertical accuracy of topographic map shall be not more than 10 percent of the elevation tested has one-half the contour interval, this is for paper map. For digital topographic map, vertical accuracy is describe as:

\[
RMSE_z = \sqrt{\frac{3 \times (z_{\text{data},i} - z_{\text{check},i})^2}{n}}
\]

where:
- \(z_{\text{data},i}\) and \(z_{\text{check},i}\) are check point of elevation coordinates of the i th in the dataset
- \(z_{\text{check},i}\) are check point of elevation coordinates of the i th in the independent source of higher accuracy
- \(n\) is the total number of check point
- \(i\) is an integer ranging from 1 to n
Based on the assumption that systematic errors have been eliminated and vertical errors are normally distributed, a factor of 1.9600 is used to calculate vertical accuracy at the level of 95% confidence (Greenwalt and Schultz, 1968). Vertical accuracy (NSSDA) computed using formula:

$$\text{Accuracy}_z = 1.9600 \times \text{RMSE}_z$$

For topographic maps originated by photogrammetric technique, Weng (2002) described that there are four data sampling pattern to obtain elevation measurements; systematic, random, composite sampling and contouring. Systematic sampling is a grid based spot height measurement in regular pattern, random sampling measures heights at significant points such as along the stream, breakline or hill top. Composite sampling combined both sampling. The last sampling pattern is contouring which systematically measures contours in the whole area (Weng, 2002), this mode of measurement yields significantly lower accuracy than the first three method (Petrie, 1990; Shearer, 1990 in Weng, 2002) but this method can be used to calculate the vertical accuracy of topographic map. The vertical RMSE can be computed as follows:

$$1.645 \times \text{RMSE} = \frac{\text{contour interval}}{2}$$

And,

$$\text{RMSE} = 0.304 \times \text{contour interval}$$

Table 5.4. Vertical accuracy of topographical map based on contour interval (Maune, 2001 in Rahman, 2006)

<table>
<thead>
<tr>
<th>NMAS Eq. Contour interval (m)</th>
<th>NMAS – VMAS 90% confidence level (m)</th>
<th>RMSE (NSSDA) (m)</th>
<th>NSSDA Accuracy 95% confidence level (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.305</td>
<td>0.152</td>
<td>0.091</td>
<td>0.183</td>
</tr>
<tr>
<td>0.610</td>
<td>0.305</td>
<td>0.183</td>
<td>0.366</td>
</tr>
<tr>
<td>1.219</td>
<td>0.610</td>
<td>0.366</td>
<td>0.732</td>
</tr>
<tr>
<td>1.524</td>
<td>0.762</td>
<td>0.457</td>
<td>0.914</td>
</tr>
<tr>
<td>3.048</td>
<td>1.524</td>
<td>0.914</td>
<td>1.829</td>
</tr>
</tbody>
</table>

Table 5.5. Flying height, minimum possible ci and height accuracy (Petrie, 1990 in Weng, 2002)

<table>
<thead>
<tr>
<th>Flying Height (m)</th>
<th>Minimum possible contour interval (m)</th>
<th>RMSE (90%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000</td>
<td>0.5 ~ 1.0</td>
<td>0.25 ~ 5.0</td>
</tr>
<tr>
<td>5,000</td>
<td>2.5 ~ 5.0</td>
<td>1.25 ~ 2.5</td>
</tr>
<tr>
<td>10,000</td>
<td>5 ~ 10.0</td>
<td>2.5 ~ 5.0</td>
</tr>
<tr>
<td>15,000</td>
<td>7.5 ~ 15.0</td>
<td>3.75 ~ 7.5</td>
</tr>
</tbody>
</table>
5.6. DTM Construction

In this research DTM was constructed in 4 working step: data preparation and editing, interpolation, DTM quality assessment and DTM - dike integration. The data source of the DTM is the digital contour map from the topographic map scale 1:10,000 with contour interval 5 m mapsheet: 1608-13C4,C5,D5,D4,E4, E5; 1608-14A4,A5; 1608-41C1,D1,E1; 1608-42a1, published by Bakosurtanal in 1999. As shown in the fig 5-4, we can see the study area and surrounding is located in relatively flat terrain and from contour lines that the height difference of the terrain is below 5 m. We can also find that the spotheights in this area are well distributed. The difference value of each spot height is in two number of decimal fraction its mean the difference height from each spotheight are in order of centimeter. This indicated that elevation data from the study area are adequate to build the DTM as refer to table 5-1.

In the data preparation and editing the selection of topographic data was done, Several topographic maps as mention previously, have been selected to cover the study area, the coverage is surrounding of the mud volcano vent and the area where estimated will have inundated by mud flow. In this step editing process was done, the contour line first transformed into DTM by implemented simple interpolation method such as TINs, and the result DTM then to be checked whether there was an overvalued or undervalued elevation pixel. Fig 5-8a. below show overvalued and undervalued pixel because an error in the contour database. The corrections on the contour database have to be taken to restore the correct value.

Interpolation of elevation data was using four type method which available in the DTM software. There are Triangulated Irregular Network with linear interpolation (TIN), Minimum curvature, Inverse distance weighted and Kriging with linear variogram. The parameters which are used in this step are shown in table below:
Table 5-6. Algorithm and interpolation parameters used in this study.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Interpolation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIN with linear interpolation</td>
<td>Anisotropy ratio = 1; Anisotropy angle = 0</td>
</tr>
<tr>
<td>Minimum curvature</td>
<td>Max residual = 1.7; Max iteration = 100000; Internal tension = 0; Boundary tension = 0;</td>
</tr>
<tr>
<td></td>
<td>Relaxation factor = 1; Anisotropy ratio = 1</td>
</tr>
<tr>
<td>Inverse Distance Weighted</td>
<td>Weighting power = 2; Smoothing factor = 0; Anisotropy ratio = 1; Anisotropy angle = 0;</td>
</tr>
<tr>
<td>Krigging with linear variogram</td>
<td>Anisotropy ratio = 1; Anisotropy angle = 0; Variogram slope = 0.0298; Nugget effect = 3090;</td>
</tr>
<tr>
<td></td>
<td>Drift type: No drift</td>
</tr>
</tbody>
</table>

In the DTM quality assessment, several statistical equations have been implemented to measure the error or uncertainty of the DTM resulted from the interpolation process. The lowest value of uncertainty error will be the best DTM and used for further processing. This step is described in section 5.7. in this chapter.

The government authority has been built a dike in the surrounding area to prevent further flooding. This dike has to added to the DTM to model the mud flow in the real condition. The description of how to integrate between the DTM and dike is in section 5.8.

The work flow of DTM construction can be seen in the flow chart below,

Fig 5-9. Flow chart of DTM construction
This step resulted 4 DTMs based on the four interpolation methods that were used. The DTMs can be seen below:

Fig 5-10a. DTM created using TIN
Fig 5-10b. DTM created using Minimum Curvature
Fig 5-10c. DTM created using IDW
Fig 5-10d. DTM created using Kriging

5.7. DTM Quality Assessment

There are a number of interrelated factors that influence in the quality of the DTM; the data acquisition method, the nature of the input data and the methods use to create the DTM (Shearer, 1990 in Weng, 2002). According to USGS (1995) and Caruso (1987 in Wechsler 2006), the DTM product has three type of errors; blunder error, systematic error and random error. Blunders error are vertical errors because of collection process and usually are identified and removed before the data have been published. “Systematic errors are the result of procedures or systems used in the DTM generation process and follow fixed patterns that can cause bias or artifacts in the final DTM product” (Wechsler, 2006). These two type of errors, can usually be removed before the DTM is published, but random error remain in the data (Wechsler, 2006).

Error measurement in DTM is almost impossible because there is rarely determination of the true value of geographic feature represented in data set (Goodchild et.al. 1994; Hunter et.al. 1995; in Weng. 2002). Weng is using word ‘uncertainty’ instead of error in describing the DTM quality. DTM uncertainty is measured by comparing the original elevation with elevation in DTM. This comparison will result the height...
differences between two dataset. The better way in measuring DTM uncertainty is using statistical expression such as root mean square error (RMSE) – see below, standard deviation and mean (Weng, 2002). In his paper Weng, 2002 was used RMSE as uncertainty originated from the interpolation method when the DTM was created. Similar way was used by Wood in quantifying uncertainty in the DTM. Wood (1996) was used five parameters to calculate the uncertainty of DTM and 3 of it as described below:

5.7. 1. RMSE

The RMSE measurement is well known and most popular method to quantify the DTM uncertainty. It is also used by the USGS (USGS 1987) and the ordnance Survey (Ordnance Survey, 1992). In Woods, (1996) the RMSE reflects the differences between interpolated values from the true values or the most probable elevations which is not reflect actual elevation (Wechsler, 2006). This is a dispersion measure because it is the average deviation between two datasets (Woods, 1996). This uncertainty measurement is based on assumption that the distribution of the errors are normal with zero mean (Wechsler, 2003 in Rahman, 2006).

The RMSE is valuable of quality control statistic but does not reflect the accurate assessment of the accuracy level of the DTM represents the real elevation. This only represents how the DTM corresponds with the originate data in the field (Wechsler, 2006). This measurement does not represent the horizontal accuracy of DTM, the users should calculate the horizontal accuracy on the values that resulted from geometric correction of satellite imagery if the data derive from remote sensing method or from the horizontal accuracy of the GPS when the DTM derived from differential GPS (Rahman, 2006).

\[
RMSE = \sqrt{\frac{\sum (z_i - z_j)^2}{n}}
\]

Where \(z_i\) and \(z_j\) are two corresponding elevation values
\(n\) is the number of elevation pairs modelled

The value of RMSE is the differences between two datasets, the larger of value indicating the higher differences between two measurements (Woods, 1996). The RMSE is usually use to provide single global value of deviation, therefore there is no indication of spatial variation (Woods, 1996). Empirically that error can be spatially autocorrelated as showed by Carter (1989), Guth (1992), Woods (1993) and Moncton (1994) in Woods 1996. To overcome this problem Goodchild (1986) and Heuvelink (1993 in Woods, 1996) suggested to separate the value of spatial trends from the non spatial error.
5.7.2. Accuracy ratio

The accuracy ratio is a value that represents the result of relative relief effects elimination from deviation measurement, simply by divided RMSE with relative relief measurement. Therefore the accuracy ratio is RMSE value divided by standard deviation of elevation value (Woods, 1996).

\[
\text{Accuracy ratio } a = \frac{\sum(z_i - z_j)^2}{\sum(z_i - z_j)^2}
\]

Where \(z_i\) and \(z_j\) are measured as above
\(z_i\) is the average elevation of \(i\)

5.7.3. Mean and Standard Deviation

The mean and standard deviation are used to estimate the random error in order to assess the variability of the forecast about its mean value (Wechsler, 2006). “This measurement cannot identify non-stationary of the dataset, if the mean value is non-zero it indicates that overestimates and underestimates of elevation are not equal, and that the overall accuracy of the model can be improved simply by subtracting the mean deviation from all elevation values” (Woods, 1996).

\[
\overline{d_{z_i}} = \frac{\sum z_i - \sum z_j}{n}
\]

\[
s = \sqrt{\frac{\sum (z_i - z_j - \overline{d_{z_i}})^2}{n}}
\]

Where \(z_i\) and \(z_j\) are measured as above
\(d_{z_i}\) is the mean deviation between models
\(s\) is the standard deviation between models

5.7.4. Another DTM uncertainty measurement

Another uncertainty measurement can be assessed using several statistical estimator as shown in table below, users can be examined all or some of these measurement statistical equation (Wechsler, 2006).

Bias

\[
\text{Bias} = \frac{\sum_{i=1}^{N}(\bar{Y}_i - Y_i)}{N}
\]
Relative Bias

\[ R_{Bias} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\hat{Y}_i - Y_i}{Y_i} \right) \]

Average Relative Absolute Difference

\[ ARAD = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\hat{Y}_i - Y_i}{Y_i} \right| \]

Relative Root Mean Square Error

\[ RRMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left( \frac{\hat{Y}_i - Y_i}{Y_i} \right)^2} \]

Log Root Mean Square Error

\[ LRMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \ln \left( \frac{\hat{Y}_i}{Y_i} \right)^2} \]

Where \( \hat{Y} \) refers to the estimator of the parameter \( Y_i \) and \( N \) is the number of simulation.

5.7.5. Result and Discussion

The value of DTM uncertainty is depends on three factors, measurement of topographic map, sampling and measurement error and interpolation (Weng, 2002). The total of DTM uncertainty can be calculated using equation below:

\[ RMSE_{total} = \sqrt{(RMSE_m)^2 + (RMSE_r)^2 + (RMSE_i)^2} \]

\( RMSE_m \) = uncertainty of source map  
\( RMSE_r \) = uncertainty of sampling and measurement error  
\( RMSE_i \) = uncertainty of interpolation process

Table 5.7. Measurement of DTM uncertainty

<table>
<thead>
<tr>
<th>Interpolation method</th>
<th>TIN</th>
<th>Minimum Curvature</th>
<th>Inverse Distance Weighted</th>
<th>Krigging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computation time</td>
<td>10.9 s</td>
<td>117.1 s</td>
<td>694.9 s</td>
<td>00:27:31.9</td>
</tr>
<tr>
<td>Mean Standard Deviation</td>
<td>31.849</td>
<td>-250.375</td>
<td>4.615</td>
<td>18.012</td>
</tr>
<tr>
<td>Coef. Of variation</td>
<td>0.885</td>
<td>6.100</td>
<td>3.902</td>
<td>9.316</td>
</tr>
<tr>
<td>Coef. Of skewness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td>127.752</td>
<td>494.014</td>
<td>18.594</td>
<td>18.600</td>
</tr>
</tbody>
</table>
Table 5-7 shows the results of measurement of the DTM uncertainty in this study, four interpolation method has been implemented. The TIN interpolator has the lowest computation time, and the value of RMSE is the second lowest after Minimum curvature. Besides the result from this interpolator show triangular facets in the flat terrain indicating that data is too few in this area. Minimum curvature interpolator has the biggest RMSE, the mean is the lowest and it has the biggest uncertainties. Kriging and IDW have almost similar values of RMSE but krigging takes the longest in the computation time. The DEM resulted from IDW has terraces features on slope terrain and bull eye features in flat terrain, therefore overall krigging interpolator has the less uncertainty and highest quality of DEM in this study.

The total value of the DTM based on 1:10,000 topographic map in this study is:

Source map:
\[ RMSE_m = 0.304 \times 5 = 1.52 \]

Interpolation process:
\[ RMS_i = 18.600 \]

Total RMSE:
\[ RMSE_{total} = \sqrt{(1.52)^2 + (18.6)^2} \]
\[ = \sqrt{2.3104 + 345.96} = \sqrt{348.2704} \]
\[ = 18.66 \]

5.8. Man made terrain modeling (dike)

5.8.1. DTM – Dike integration

A Dike forms a protection of an area to flooding by acting as an obstacle to waterflow. Other objects on the surface which have similar function like obstacle such as building, elevated road, curb and another man made features. All these features will guide the flow water, and will play an important role in the flow velocity and the maximum extent of the flood.

The study area is located in urban area and man made features are everywhere. To include the elevation of man made feature is very difficult because of time and cost constraints, LIDAR and Ifsar are two types of remote sensing that can capture elevation of man made features, but since the cost are major constraint the availability of such data is very limited or even does not exist.

Data about location and boundary of dike in this study are derived from IKONOS imagery which can downloaded for free from CRISP website (www.crisp.nus.edu), from this website we can download the IKONOS imagery with lower resolution (6 m). The height of the dike is derived from monthly report map from government authority. The flow chart of integration of DTM and dike can be seen below:
Five DTM s were constructed in this study to represent 5 time scenarios of the inundation. The dates of the DTM s are the following:

- 06 June 2006 – the dike has not been built
- 29 August 2006 – the dike was broke
- 31 October 2006 – the dike was broke
- 06 December 2006 – the dike was broke
- 05 January 2007 – the dike was broke

The DTM and imagery which represents the time scenario above can be seen below:
The DTM with dike and Ikonos imagery
5.8. 2. Resolution of DTM

Resolution of DTM is important factor in flow modeling because DTM resolution indicated how detailed the DTM represents the surface relief. The resolution also plays an important role for the computation time of the simulations. Many computers with high speed computation can be found today, but since most modeling software work on raster data, the more data the slower the computation process, and of course more advanced computer technology will make the computation faster but the cost will be higher.

In this study the resolution selection that resulted in acceptable computation times, was achieved by trial and error. The final resolution was also selected by comparison between the DTMs with various resolutions. The optimal resolution was determined by the cross-section or traverse method which was implemented in some parts on the DTM. Fig 5‐13a shows the profiling from A‐B and Fig5‐13b is the height difference for each type of resolution. DTM for this study was originated from contour topographic map with 5 m contour interval. Based on the cross section and computation time needed by SOBEK software the DTM with 20 m resolution is reliable enough to represents terrain relief for this application.

![Fig 5-13a. Profiling from A-B](image1)
![Fig 5-13b. Cross section from A-B](image2)
CHAPTER 6. MUD FLOW MODELING

6.1. Governing equation

The behavior of fluid material can be described either by Newtonian or Non Newtonian Law of physics. The Newtonian fluid considered when shear stress is a linear function of the shear rate for example in flow of water, flood modeling using this principle to describe the flow of water. The non Newtonian fluid considered when the shear stress is not a linear function of the shear rate and when viscous behavior is non linear. Mud flow behavior can be described as non Newtonian fluid if the viscosity is high enough depends on the concentration of fine particle in the mixture.

The flow behavior of two type of fluid as explained above can be explained by mass and momentum conservation principle. The mass and momentum conservation equations are:

\[
\frac{\partial h}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]

\[
\frac{\partial u}{\partial t} + \frac{\partial u^2 h}{\partial x} + \frac{\partial v}{\partial y} = -g \left( h \sin \alpha_x \cos \alpha_x + h \lambda_x \frac{\partial z_f}{\partial x} - \frac{\tau_{ox}}{\gamma} \right)
\]

\[
\frac{\partial v}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v^2 h}{\partial y} = -g \left( h \sin \alpha_y \cos \alpha_y + h \lambda_y \frac{\partial z_f}{\partial y} - \frac{\tau_{oy}}{\gamma} \right)
\]

where,

- \( h \) = the flow depth
- \( (u, v) \) = depth average of flow momentum in the x and y
- \( z_f = z_b + h \) = height or vertical coordinate of the free surface (m)
- \( z_b \) = bed surface
- \( (\alpha_x, \alpha_y) \) = bed gradient in the x and y
- \( \gamma \) = bulk unit weight (KPa.m\(^{-1}\))
- \( \tau_o \) = bottom shear stress

The equations above are valid for newtonian, viscous and granular type of flows (Santiago and van Asch, 2007). The use of equation above to the type of fluid flows is depends on how the formulation of flow resistance term and generally non Newtonian fluid will use the definition of the Herschel-Bulkley model (Santiago and van Asch, 2007) and can be described by the following equation:

\[
\tau = \tau_y + \mu \left( \frac{\partial \varepsilon}{\partial t} \right)^m
\]
where,
\( \tau \) = shear stress (KPa)
\( \tau_y \) = yield strength
\( \frac{\partial \varepsilon}{\partial t} \) = strain rate
\( \mu \) = coefficient of dynamic viscosity (kPa.s)

m is an empirical parameter which has to be determined in Herschel-Bulkley model and equal zero for Bingham model and this model can be used to described mud flow.

The Newtonian fluid such as water described using shallow water equation based on Saint Venant equation like used in SOBEK. The shallow water equation can be described using following relation:

\[
\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}
\]

where,
\( A_f \) = wetted area
\( q_{lat} \) = lateral discharge per unit length (m²/s)
\( Q \) = discharge (m³/s)
\( t \) = time (s)
\( x \) = distance (m)

SOBEK using integration of 1D and 2D hydrodynamic modelling which using the following equation:

Momentum equation 1D flow:

\[
\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} \left( \frac{Q^2}{A_f} \right) + g.A_f \cdot \frac{\partial h}{\partial x} + \frac{qQ |Q|}{C^2 R A_f} - W_f \cdot \frac{\tau_{wi}}{\rho_w} = 0
\]

where,
\( A_f \) = wetted area (m²)
\( q_{lat} \) = lateral discharge per unit length (m²/s)
\( Q \) = discharge (m³/s)
\( t \) = time (s)
\( x \) = distance (m)
\( g \) = gravity acceleration (≈ 9.81 m/s²)
\( h \) = water level (m)
\[ C = \text{chezy coefficient (m}^{1/2}/\text{s}) \]
\[ R = \text{hydraulic radius (m)} \]
\[ Wf = \text{flow width (m)} \]
\[ \tau_{wi} = \text{wind shear stress (N/m}^2) \]
\[ \rho_w = \text{water density (kg/m}^3) \]

Continuity equation 2D flow:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0
\]

where:
\[ u = \text{velocity in x-direction (m/s)} \]
\[ v = \text{velocity in y-direction (m/s)} \]
\[ V = \text{velocity: } V = \sqrt{u^2 + v^2} \]
\[ \zeta = \text{water level above plane of reference (m)} \]
\[ h = \text{total water depth: } \zeta + d \text{ (m)} \]
\[ d = \text{depth below plane of reference (m)} \]

Momentum equation 2D flow:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + g \frac{d\zeta}{x} + g \frac{|V|}{C^2 h} + au |u| = 0
\]
\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + g \frac{d\zeta}{x} + g \frac{|V|}{C^2 h} + av |v| = 0
\]

where:
\[ u = \text{velocity in x-direction (m/s)} \]
\[ v = \text{velocity in y-direction (m/s)} \]
\[ V = \text{velocity: } V = \sqrt{u^2 + v^2} \]
\[ \zeta = \text{water level above plane of reference (m)} \]
\[ h = \text{total water depth: } \zeta + d \text{ (m)} \]
\[ d = \text{depth below plane of reference (m)} \]
\[ a = \text{wall friction coefficient (1/m)} \]
\[ C = \text{chezy coefficient (m}^{1/2}/\text{s}) \]
6.2. Software

In the flow modeling the selection of the software is primarily based on the characteristics of flow material. There are three type of flow material based on flow category, streamflow, slurry and granular flow (Alkema, et.al, 2006). These type of flow categories are classified based on concentration of water and fine material. If the concentration of water exceeds 70% it has category as streamflow like water and mud flows, and if water content decreases until 80 % it has category as slurry flow for example debris and solifluction. For every flow category there is the law of physics which works either Newtonian or Non-Newtonian. Newtonian law of physics used to describe mostly water with low viscosity and its flow behavior are determined by friction, while the flow of water with very high particle content and high viscosity are determined by Bingham flow (Alkema, et.al, 2006).

Both type of material flow as explained above were implemented into different software. SOBEK is software for hydrodynamic modeling developed by Delft Hydraulics is used to model water flow material. Water with very high particle content and high viscosity can be modeled using PC raster, an open source software developed by University of Utrecht the Netherlands. As an open source software PC raster has capability to incorporate the design of flow material based on flow properties which is defined by users, but SOBEK as built in software is a ‘black box’ system which required an initial knowledge of the software.

In this study mud volcano as flow material has specific properties which is very unique depends on its location and its geological characteristics. For example in several literature mud volcanos are have high viscosity and density but in this case the density is almost the same with water (1.4 gr/cm3) and it viscosity is relatively low (1.4 N.s). So this phenomenon is relatively new because there was limited research previously conducted.

PC raster which allows users to make their own designed model using programming script is very useful and ideal tool to model the flow behavior of mud volcano. For this reason PC raster was previously use in this study, but there are some limitation causing this work was not successful. The first constraint is there were no script has been developed for mud volcano, while to develop the new script is takes a long time which is beyond the time limit of M.Sc study. The second reason is inside the developer of PC raster itself, such flow phenomenon which called ‘diffusive flow’ is under construction (Jetten, lecture notes 2006), therefore this research in the future could be one of the ‘study case’. In order to make a good model of mud volcano it required deep study of mud flow properties such as viscosity, the yield strength and its temperature, and this will be fulfilled if there is enough time.

SOBEK was selected to replace PC raster software based on the properties of mud volcano which has density similar with water and has low viscosity. The similar research was done by Martini, et.al, 2003, which conducted research on the flood flows and suspended sediment transport in the Brenta River, Italy. Martini, et.al was used ID2D hydrodynamic modeling based on the Saint Venant equation.
6.3. Input Parameters

SOBEK has powerful module to define an input data called NETTER. In this module users can define input data graphically using advance graphical user interface or GUI. NETTER also has a tool to attach vector file or image as a background so user can define input data easier. SOBEK required several input data such as:

- Elevation data (DTM)
- Simulation period and time steps
- Dimension of the channel
- Water level
- Discharges of water
- Coefficient of roughness

![Fig 6-1. The graphical user interface (GUI) in SOBEK](image)

The process of input data in SOBEK are in two steps, first is defined input for 1D feature such as river or channel and the second is input for 2D feature such as overland flow. The 1D feature like river or channel is defined using 1D nodes and it called flow model, and this nodes connected as network using straight line connector called reaches. The reach segment has function as flow model or overland flow model connector. The whole input which contain node and reaches then work together as network and simulates the flow modeling.

In this study the data input are the DTM, discharge of mud flow and the cross section of the channel. As a matter of fact there was no channel in the field except the channel of gas exploration or the well bore. In SOBEK users has to define the channel dimension in 1D module, for this reason the channel dimension defined.
6.4. Output Parameters

Output parameters in SOBEK can be classified into three type, there are water depth, water level and velocity. This output parameter then can be displayed or analyzed as GIS map, and contains the following variables (SOBEK hlp):

- maximum water depth (d_max)
- time of maximum water depth (t_dmax)
- maximum water level (h_max)
- time of maximum water level (t_hmax)
- maximum velocity (v_max)
- time of maximum velocity (t_vmax)
- time of wetting (t_wet)
- time of wetting per class (steady state') (t_wet/class)
- time of drying (t_dry)
- time of drying per class (steady state') (t_dry/class)
- rate of change of water depth (dd/dt)
SOBEK also provide an output result as time series output files in ascii format (*.asc). SOBEK will create the series output files only when users choose water depth, water level and velocity checkbox is switched on. This will create many files representing some parameters as stated before. The number of files which will create are depend on the number of time steps of the simulation, for example if users make 24 hours simulation with one minute time step so the output maps creates by SOBEK will be 24x5x60 equals 7200 output files.

6.5. Initial and Boundary condition

In SOBEK initial condition is the initial input defined by users, there are two type of initial condition, the depths or water levels and the discharges at the beginning of the simulation. One of the initial condition must be defined first, but users are allows to use both, for example at certain model there are specific discharges at the beginning of simulation but it has also water inundation at certain level. In such cases the program will first filled up the area with water at certain level and then the simulation will start further from that level. The simulation also can be built from the result of another simulation, the initial simulation which is save in ‘restart file’ will be the basis of the next simulation.

In this study the initial condition was the discharges from the point of eruption, and the water level starts from zero, it means this is completely dry system. Mud volcano in this study was come up to the surface from below because of a failure of gas exploration activity, therefore the simulation was start from completely dry condition to inundated.

![Fig 6-5. Model simulation to be set as completely dry system](image)

Boundary condition is represents the external flow or the amounts of water come up in the system. Boundary condition can be specified as water level, discharge, depth or as rating curve. There is also an option to specify the boundary condition as time series input. For this model a discharge of mud flow is defined as boundary condition. The discharge is defined in the 1D boundary node which represents an eruption vent of
mud volcano. Several discharges were defined to model several dike breaks in five different scenarios as explained in scenario arrangement sub topic.

Fig 6-6. Input parameters of Boundary condition.

6. 6. Surface roughness

Surface roughness has function as a resistance force in the flow equation and used to represent the bottom friction. There are several type of surface roughness use in SOBEK, chezy, strickler, Colebrook, manning, and commonly used to represent the surface roughness of floodplain and channel (Tennakoon, 2004).

In this study manning’s roughness was used as an input of surface roughness. The manning coefficient was derived from land use map of 1:25.000 produced in 1996 and updated using IKONOS imagery of 2002. The manning’s equation is expressed as :

\[ V = \left( \frac{R^{2/3} \times S^{1/2}}{N} \right) \]

where,

\( V \) = Flow velocity (m/sec)
\( R \) = Hydraulic radius (m)
\( S \) = Channel gradient
\( N \) = Mannings roughness coefficient

The land use map with an attribute contains manning coefficient then converted into raster file format using ILWIS, this raster map then exported into ASCII file format and use as an input in SOBEK.
Fig 6-7. Land use map as input of manning roughness

Fig 6-8. Ikonos image as input for land use update

Fig 6-9. Land use map as manning coefficient map

Tabel 6-1. Manning coefficient derived from Land use map

<table>
<thead>
<tr>
<th>NO.</th>
<th>LAND USE TYPE</th>
<th>MANNING COEFFICIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barren Land/Open Space</td>
<td>0.0200</td>
</tr>
<tr>
<td>2</td>
<td>Built up area</td>
<td>0.1500</td>
</tr>
<tr>
<td>3</td>
<td>Fish pond</td>
<td>0.0200</td>
</tr>
<tr>
<td>4</td>
<td>Grassland</td>
<td>0.0300</td>
</tr>
<tr>
<td>5</td>
<td>Mix Garden</td>
<td>0.0350</td>
</tr>
<tr>
<td>6</td>
<td>Paddy field</td>
<td>0.0300</td>
</tr>
<tr>
<td>7</td>
<td>Pavement, Asphalt or Concrete</td>
<td>0.0130</td>
</tr>
<tr>
<td>8</td>
<td>Plantation (Sugar cane)</td>
<td>0.0350</td>
</tr>
<tr>
<td>9</td>
<td>River</td>
<td>0.0300</td>
</tr>
<tr>
<td>10</td>
<td>Settlement</td>
<td>0.1000</td>
</tr>
<tr>
<td>11</td>
<td>Shrub</td>
<td>0.0600</td>
</tr>
<tr>
<td>12</td>
<td>Swamp</td>
<td>0.0600</td>
</tr>
<tr>
<td>13</td>
<td>Waterbody/Sea</td>
<td>0.0300</td>
</tr>
</tbody>
</table>

6.7. Model schematization

The first step to create simulation in SOBEK is Model Schematization, in this step users designed the network and the attribute of each nodes, reach segments, cross section data and boundary condition. River and channel must be defined in 1D network. The 1D network is constructed from boundary nodes, connection segments, cross sections and calculation points. The 2D network is constructed from several elements such as nodes and reaches segments, and in the 2D network the boundary conditions such as water level and discharge are determined.

The elevation data such as DTM is imported from ASCII file format. The DTM will read in SOBEK as a set of grid, each grid can be determined as single value of roughness or one value of roughness for the whole grids. The value of roughness could be defined as variable with reference to the land use map.

In this study the schematization was built by determine flow boundary node which connected to another flow module node by reach segment. The Cross section node will be defined in the flow segment and acting like a small channel to flow a certain numbers of discharges. This is the basic procedure in 1D module in SOBEK, without this the simulation will not work. In real condition there is no channel in the field, because in this study mud flow was come up from well bore below the surface.

Several history stations were defined in the surrounding area to calculate the velocity and the depth of the mud flow. These stations are built inside and outside the dike. The stations inside the dike are to calculate flow parameter when mud flow fulfilled the dike, and when the dike broke or overtopped the stations outside the dike will do calculation.

At a certain location the elevation of dike was built half to one meter lower to simulate the broken dike. The mud flow from this point will inundate the area surrounding and SOBEK will simulate the flood extent.
6.8. Scenario arrangement

Mud flow in this study has been occurred for almost two years, and the dike which is built area surrounding to prevent from flooding has been broke many times. This study is intended to model the mud flow by simulating the area inundated when the dike was broke. Five scenarios of inundated events in the area were chosen based on the availability of the data to verify. The available data were used to modeled mud flow are Ikonos imagery and the published maps.

The scenarios of the model are described in the table below:

<table>
<thead>
<tr>
<th>No.</th>
<th>Date of event</th>
<th>Discharge (m³/day)</th>
<th>Discharge (m³/s)</th>
<th>Simulation time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29-May-06</td>
<td>50,000</td>
<td>0.578</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>11-Jun-06</td>
<td>50,000</td>
<td>0.578</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>29-Aug-06</td>
<td>120,000</td>
<td>1.388</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>31-Oct-06</td>
<td>120,000-126,000</td>
<td>1.388-1.458</td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>6-Dec-06</td>
<td>120,000-126,000</td>
<td>1.388-1.458</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>5-Jan-07</td>
<td>120,000</td>
<td>1.388</td>
<td>30</td>
</tr>
</tbody>
</table>

Fig 6-10. Schematization of the model
There are some basic assumption were implemented in this model due to very complicated condition in the field. Some human activity to control the mud flow has been done and therefore the behavior of mud flow is not totally natural. The first assumption was the discharge of mud flow to be determined as constant value during the modelling process because there is no record of discharge changes from time to time. The only available record is from ‘Media Center Lusi’, one of official News media from government to provide the news of this hazard event.

The second assumption was the water level defined as zero height or the system assumed as completely dry. It means for every model scenario the initial condition is start from zero water levels and water will come up in certain level following the discharge. The water then spilled out or overtopped after reach a certain elevation of dike and this simulate as mud flow.

The value and magnitude of land subsidence in this model were ignored, this because of the pattern and magnitude of the subsidence were random in this area (Abidin, et.al, 2006).

This study was focused on the behavior of flowing of mud volcano, therefore the major concern was the characteristics of mud flow such as the extent of inundated area, the depth and the velocity of flow.

6. 9. Modeling Result

In SOBEK the output of flow modeling is inundation extent, depth and flow velocity. All output is in time series file and can be converted into GIS file format, therefore modeling analysis using this software is easier and can integrate with another GIS software for further analysis.

6.9. 1. Inundation Extent

There are five output of inundation extent based on scenario arrangement and then the result to be compared with reported map which represents actual events. Fig 6-11. below showed five output inundation extent maps for five time scenarios. From these results area of inundation extent are to be calculated and to be compared with area of inundation extent from reported map.
Table 6-3. consist of comparison of the area of inundation between the actual event and the model. The overlapped area also calculated to see how large area between the actual events with the model. The percentages of area overlap show how good the flow model represents the actual events. This simple analysis was tried to find out whether SOBEK can simulate mud flow or not, and whether the mud flow can be assumed have characteristics similar with water or not.

Fig 6-12 and Fig 6-13 showed comparison between mud flows recorded from IKONOS imagery with flow modeling result. The figures showed that overlap area is the area of mud flow which represents both actual event and modeling event.

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>06 June 2006</td>
<td>Flow modeling result for five time scenarios.</td>
</tr>
<tr>
<td>29 August 2006</td>
<td></td>
</tr>
<tr>
<td>31 October 2006</td>
<td></td>
</tr>
<tr>
<td>06 December 2006</td>
<td></td>
</tr>
<tr>
<td>05 January 2007</td>
<td></td>
</tr>
</tbody>
</table>
Fig 6-12. Inundation extent on 06 June 2006

Fig 6-13. Inundation extent on several time scenarios
Table 6-3. Comparison result between inundation area and area from the model

<table>
<thead>
<tr>
<th>No.</th>
<th>Date of event</th>
<th>Data comparison source</th>
<th>Area Actual ( (m^2) )</th>
<th>Area Modeling ( (m^2) )</th>
<th>Area Overlap ( (m^2) )</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11-Jun-06</td>
<td>Reported Map</td>
<td>471986.71</td>
<td>3770941.201</td>
<td>99646.48</td>
<td>21.11214</td>
</tr>
<tr>
<td>2</td>
<td>29-Aug-06</td>
<td>Ikonos image</td>
<td>48648.178</td>
<td>347644.597</td>
<td>35515.601</td>
<td>73.005</td>
</tr>
<tr>
<td>3</td>
<td>31-Oct-06</td>
<td>Ikonos image</td>
<td>141681.661</td>
<td>1023800</td>
<td>70526.49</td>
<td>49.77814</td>
</tr>
<tr>
<td>4</td>
<td>6-Dec-06</td>
<td>Ikonos image</td>
<td>851547.709</td>
<td>1383112.445</td>
<td>367760.455</td>
<td>43.1873</td>
</tr>
<tr>
<td>5</td>
<td>5-Jan-07</td>
<td>Ikonos image</td>
<td>1365194.356</td>
<td>906313.991</td>
<td>563413.092</td>
<td>41.2698082</td>
</tr>
</tbody>
</table>

Based on the table above we can see that the result of overlap area has percentage difference ranges from 21 % to 73 % but mostly with 40% overlap, from this point the flow modeling using SOBEK represents 40% of area inundated by mud flow. This result probably because of no input of building height and elevation data of man made structure such as road, irrigation channel, curb etc. Such man made features plays important role as obstacle and friction force and influence to inundation extend. The building footprint was treated as surface roughness and the result indicated wider inundation area comparing with the result which use original value of manning coefficient as explained in the model calibration.

The value of mud flow velocity also plays role primarily on the flow velocity, viscosity defined as fluid’s internal resistance to flow and influence to lower flow velocity. Therefore viscosity also influences the inundation extent.

6.9. 2. Depth of Inundation

The depth of inundation is also one of output parameter in SOBEK. By comparing the result from flow model and actual event we can also find out whether SOBEK can simulate the mud flow or not. In the figures below there are five maps of inundation depth for five time scenario, only three of them to be compared with actual depth of inundation because there were only three recorded data which match with the time scenario of the model. The data of inundation depth was come from PT. Lapindo Brantas, the gas exploration company.

Fig 6-14 to Fig 6-16 showed that only Fig 6-14 show the depth of inundation on 29 august 2006 has a good match with recorded data except in the central eruption where the recorded data has deeper elevation. There are probably because of several causes:

- land subsidence, in the field there were subsidence occurred which has random magnitude and direction, in the model this factor was ignored
- the DTM resolution, in order to maintain the optimum result of computation time, the DTM resolution was resample into certain value (20 m) and this will caused the terrain relief reduced
- the DTM quality, the DTM input of the model was generated from 1:10.000 topographic maps which has 5 m contour interval, in flat terrain the spot height
was added to represents the difference of elevation, probably this spot heigh was not adequate and additional measurement of spot heigh is necessary.

Fig 6-14. Comparison of inundation depth at 29 August 2006

Fig 6-15. Inundation depth map at 11 June 2006
Spatial Modelling and Risk Assessment of Sidoarjo Mud Volcanic Flow

**October 29, 2006**

**Fig 6-16.** Comparison of inundation depth at 31 October 2006

**Fig 6-17.** Inundation depth map at 27 January 2006
6.9.3. Flow velocity

Similar to the inundation depth the flow velocity of the model also computes at every timestep of simulation and converted into GIS file format. In Figure 6-19 and Figure 6-20 can be seen the result of flow velocity variation for five time simulation scenarios. The result of flow velocity shows that five simulation scenarios have the same value and indicated that flow velocity influenced mainly by slope of the terrain. Unfortunately there were observed data from the field to verify this result.

The flow velocity is important aspect to calculate kinetic energy resulted from flood event, and this is main parameter to determine the potential damage in the area.
Fig 6-19. Velocity map on 11 June 2006

Fig 6-20. Velocity maps for four different simulation scenarios
6.9.4. Computation time

The computation time is one of major limitation in flow modeling. Mostly flow modeling consume a large number of time depend of the pixel resolution and the area coverage of modeling extent. In SOBEK the computation time also depend on simulation periods and time steps of computation. Therefore users has to be determined the resolution, coverage area and the computation time steps in order to get the optimum time of computation and the result expected.

In this study several initial run of modeling has been done in order to get the optimum parameters of computation before the ‘real modeling’ was run. The result of computation of this study can be seen in the table below:

Table 6-4. The computation time for each modeling scenario

<table>
<thead>
<tr>
<th>No.</th>
<th>DTM</th>
<th>Res (m)</th>
<th>Number of pixel</th>
<th>Simulation periods (days)</th>
<th>Time steps output</th>
<th>Number of time steps</th>
<th>Time of computation (hrs:min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11-Jun-06</td>
<td>25</td>
<td>263x260</td>
<td>15</td>
<td>1 hrs</td>
<td>1057</td>
<td>0:34:32</td>
</tr>
<tr>
<td>2</td>
<td>29-Aug-06</td>
<td>20</td>
<td>412x256</td>
<td>60</td>
<td>1 hrs</td>
<td>2977</td>
<td>7:53:51</td>
</tr>
<tr>
<td>3</td>
<td>31-Oct-06</td>
<td>20</td>
<td>200x215</td>
<td>60</td>
<td>1 hrs</td>
<td>2833</td>
<td>9:08:33</td>
</tr>
<tr>
<td>4</td>
<td>6-Dec-06</td>
<td>20</td>
<td>175x193</td>
<td>60</td>
<td>4 hrs</td>
<td>4321</td>
<td>5:32:23</td>
</tr>
<tr>
<td>5</td>
<td>5-Jan-07</td>
<td>20</td>
<td>178x191</td>
<td>60</td>
<td>5 min</td>
<td>17857</td>
<td>10:03:07</td>
</tr>
<tr>
<td>6</td>
<td>DTM for Risk Assessment</td>
<td>30</td>
<td>411x250</td>
<td>60</td>
<td>1 hrs</td>
<td>1417</td>
<td>2:45:22</td>
</tr>
</tbody>
</table>

6.10. Model Calibration and Validation

Model calibration was conducted in this study by implemented three scenarios with three different values of manning roughness coefficient. The first scenario was using the value roughness of manning coefficient which was compiled from several literatures, the second scenario was using manning coefficient which has value 25% higher from the first scenario. The third scenario was using the value of manning coefficient of the first scenario but also including the manning coefficient of building footprint. Data of building footprint was generated from topographic map scale 1:10.000 which updated using IKONOS imagery of 2002.

Three scenarios of different manning coefficient were implemented to find out the correct value of roughness coefficient in the study area. While building footprint was added to get the real impact of buildings and houses in the modelling. The building footprint was acted as roughness surface rather than three dimensional objects in the field because the three dimensional data of buildings and houses were not available.
Table 6-5. showed three different value of manning coefficient which implemented in the calibration process.

Table 6-5. Manning coefficient value for calibration process

<table>
<thead>
<tr>
<th>NO.</th>
<th>LAND USE TYPE</th>
<th>Initial Run</th>
<th>Calibration 1</th>
<th>Calibration 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barren Land/Open Space</td>
<td>0.020</td>
<td>0.025</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>Built up area</td>
<td>0.150</td>
<td>0.1875</td>
<td>0.225</td>
</tr>
<tr>
<td>3</td>
<td>Fish pond</td>
<td>0.020</td>
<td>0.025</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>Grassland</td>
<td>0.030</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>5</td>
<td>Mix Garden</td>
<td>0.035</td>
<td>0.0438</td>
<td>0.0525</td>
</tr>
<tr>
<td>6</td>
<td>Paddy field</td>
<td>0.030</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>7</td>
<td>Pavement, Asphalt or Concrete (Road)</td>
<td>0.013</td>
<td>0.0163</td>
<td>0.0195</td>
</tr>
<tr>
<td>8</td>
<td>Plantation (Sugar cane)</td>
<td>0.035</td>
<td>0.0438</td>
<td>0.0525</td>
</tr>
<tr>
<td>9</td>
<td>River</td>
<td>0.030</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>10</td>
<td>Settlement</td>
<td>0.100</td>
<td>0.125</td>
<td>0.15</td>
</tr>
<tr>
<td>11</td>
<td>Shrub</td>
<td>0.060</td>
<td>0.075</td>
<td>0.09</td>
</tr>
<tr>
<td>12</td>
<td>Swamp</td>
<td>0.060</td>
<td>0.075</td>
<td>0.09</td>
</tr>
<tr>
<td>13</td>
<td>Waterbody/Sea</td>
<td>0.030</td>
<td>0.025</td>
<td>0.045</td>
</tr>
<tr>
<td>14</td>
<td>Building footprint (single building)</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

In the calibration process the parameters used in the modelling were:
- DTM resolution is 20 m, in this resolution modeling result was showed the highest sensitivity as explained in sensitivity analysis sub topic.
- The inundated scenario is using the sixth scenario (5 January 2007) as described in the scenario arrangement because this scenario has the most complicated terrain of DTM.
- The discharge is 1.4 m³/s
The result of calibration then analyzed by comparing the inundation extend and the flow velocity. As we see in the Fig 6-22, the first scenario showed the lower inundation extends and higher flow velocity compared to another scenarios. The second and the third result showed the bigger inundation extend indicated the surface roughness act as obstacle on the surface and made inundation spread wider. The value of building footprint as the highest of surface roughness gives significant effect on the flow model, from the result we can see the inundation extend was wider than the second scenario.

In the model calibration we found that roughness coefficient has an important role in flow behavior, by implementing the right value we will get the appropriate result which can construct the real event in the field. But in this study we still get the result which has different inundation extent compared to the real events, this probably because of the different characteristics of flow material. The real event is the mud flow which has different viscosity with water. The value of viscosity acts as friction force which makes the velocity of flowing slower.

Another reason regarding to different result is the detail terrain of study area were not captured well enough in the topographic maps. The topographic maps is in scale of 1:10,000 which has 5 m contour interval, it means topographic maps can only represents the relief which has 5 m different elevation. In steep elevation this maps is
adequate as input data of flow modeling, but in flat terrain like in the flood plain it requires additional measurement of spot height.

In this study the topographic maps has many spotheight to represent the detail of relief and the different of each spotheight is in order of centimeters unit, but the distance between one spotheight to another is in the range of 100 – 250 m, this is probably the reason why the spotheight could not represent the detailed of the relief. From this point additional measurement of elevation data are necessary, but due to condition in the field a new measurement is not possible.

6. 11. Sensitivity analysis

Sensitivity analysis was done using all parameters used in the modelling. The parameters have been used in this study were DTM resolution, discharge of the eruption of mud volcano and surface roughness. Sensitivity analysis also implemented to each of parameters and one of them will explain in the following sub topic and the rest parameters can be seen on the appendices.

Sensitivity of the model was analyzed by inputting varying value of each parameter and observed the result of the model. Every parameter was designed into 5 categories, each category has value different 25%, for example the discharge value used is 0.5, 0.75, 1, 1.25 and 1.5 m3/s. The DTM used is DTM with resolution of 10, 15, 20, 25 and 30 m. The manning coefficient also designed into 5 categories, the first value was derived from literatures and another was designed into value of 25% lower and 25% higher. Table 6-6. below showed the manning coefficients used for sensitivity analysis.

Table 6-6. Manning coefficient for sensitivity analysis

<table>
<thead>
<tr>
<th>NO.</th>
<th>LAND USE TYPE</th>
<th>25% Lower</th>
<th>50% Lower</th>
<th>Normal value</th>
<th>25% Higher</th>
<th>50% Higher</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barren Land/Open Space</td>
<td>0.015</td>
<td>0.01</td>
<td>0.02</td>
<td>0.025</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>Built up area</td>
<td>0.1125</td>
<td>0.075</td>
<td>0.15</td>
<td>0.1875</td>
<td>0.225</td>
</tr>
<tr>
<td>3</td>
<td>Fish pond</td>
<td>0.015</td>
<td>0.01</td>
<td>0.02</td>
<td>0.025</td>
<td>0.03</td>
</tr>
<tr>
<td>4</td>
<td>Grassland</td>
<td>0.0225</td>
<td>0.015</td>
<td>0.03</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>5</td>
<td>Mix Garden</td>
<td>0.0263</td>
<td>0.0175</td>
<td>0.035</td>
<td>0.0438</td>
<td>0.0525</td>
</tr>
<tr>
<td>6</td>
<td>Paddy field</td>
<td>0.0225</td>
<td>0.015</td>
<td>0.03</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>7</td>
<td>Pavement, Asphalt or Concrete (Road)</td>
<td>0.0098</td>
<td>0.0065</td>
<td>0.013</td>
<td>0.0163</td>
<td>0.0195</td>
</tr>
<tr>
<td>8</td>
<td>Plantation (Sugar cane)</td>
<td>0.0263</td>
<td>0.0175</td>
<td>0.035</td>
<td>0.0438</td>
<td>0.0525</td>
</tr>
<tr>
<td>9</td>
<td>River</td>
<td>0.0225</td>
<td>0.015</td>
<td>0.03</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
<tr>
<td>10</td>
<td>Settlement</td>
<td>0.075</td>
<td>0.05</td>
<td>0.1</td>
<td>0.125</td>
<td>0.15</td>
</tr>
<tr>
<td>11</td>
<td>Shrub</td>
<td>0.045</td>
<td>0.03</td>
<td>0.06</td>
<td>0.075</td>
<td>0.09</td>
</tr>
<tr>
<td>12</td>
<td>Swamp</td>
<td>0.045</td>
<td>0.03</td>
<td>0.06</td>
<td>0.075</td>
<td>0.09</td>
</tr>
<tr>
<td>13</td>
<td>Waterbody/Sea</td>
<td>0.0225</td>
<td>0.015</td>
<td>0.03</td>
<td>0.0375</td>
<td>0.045</td>
</tr>
</tbody>
</table>
The result of flow models then to be plotted into linier graphic chart to find out which parameters was the most sensitive in the model. Fig 6-23. below showed that for flow model in this study the parameter of manning coefficient is the most sensitive to the velocity of flow and depth of inundation.

Sensitivity analysis also have been implemented into each group of parameters, for example for parameter of DTM resolution, there were five different value of DTM resolution have been used. Through this analysis we try to find out the value of DTM resolution which has the most sensitive in the model.
Fig 6-25 and Fig 6-26. below showed the linear graphic chart of various value of DTM resolution respect to the flow velocity and depth of inundation. For both velocity and depth the 20 m resolution DTM was have the most sensitive in the model. Another result of sensitivity analysis can be found in the appendices.

Fig 6-25. Sensitivity graph between resolution of DTM and depth of inundation

Fig 6-26. Sensitivity graph between resolution of DTM and flow velocity
CHAPTER 7. IMPACT ASSESSMENT

7.1. Inundation Map

Impact assessment in this chapter are describing the characteristics of mud volcanic flow in the study area, the flow behavior like the depth, velocity and duration of inundation and the influence of this hazard to the element at risk in the surrounding area.

As explained in the chapter 3 mud volcanic flow is a geological phenomenon which caused of eruption of gas, water and clay out of surface. The mixture of water and clay causing flood which has longer time duration compared with stream flood or another type of flood. In this case geologist and geophysicist based on seismic and gravity data have calculated the potential reservoir of mud volcano in the subsurface were 1,155 billion cubic feet and if the average discharge of mud flow were 100,000 m$^3$ per day, then the mud flow will be stopped or finished in 31 years (Media center Lusi, 2006). This is an enormous value of inundation time, and the study of such flooding has never been conducted before. Therefore the inundation map in this study was designed in the period of 30 days, in such period predicted that government and people be able to evacuate themselves to safer location.

Inundation map was generated from flow modeling and designed using 30 m resolution of DTM and cover an area wider than the area used to model flow characteristics. For this reason resolution of DTM was reduced into 30 m, this also to maintain computation time in range of reasonable value. In the chapter 6 is explained how the coverage area and the resolution influence the time of computation. Therefore in this case it was impossible to set the timesteps of simulation in longer periods such as one or two years. In this study the timesteps for inundation map was set into 30 days of inundation simulation.

The inundation map was used the DTM with no dike surrounding, this scenario has purpose to simulate the depth and magnitude of inundation when there are no dike has been built and therefore we able to predict which area will be inundated for the first 30 days. From this point people who located inside inundation area could be warned to evacuate their families and belonging so they can minimize properties loss and damage.

Figure 7-1 showed the result of inundation simulation for first 10 days, 20 days and 30 days. The designed of inundation simulation into 3 periods was based on the priority of warning time so people will know when they should to evacuate. The 10 days simulation was determined to be the first zone, 20 days inundated simulation was the second zone and 30 days simulation was defined as the third zone.
Fig 7-1. The inundation simulation scenario in 10 days, 20 days and 30 days.

Fig 7-2. The Inundation map
The Fig 7-2. above is inundation maps in three different time scenarios which then to be defined as different zoning area as explained before. This zonation is very useful to help government to manage the hazard in the first 30 days. These zones are represents the level of danger from every area located in each zone and can be used as input data for local government to determined the buffer area and protect the area from utilization by people in the future.

7.2. Maximum Depth

Generally people use the depth of inundation as primary indication the level of flood hazard. Visually we can see the severity of flood hazard from the depth of inundation. The depth and velocity usually work together as substitute parameter, one become opposite to the other, for instance flooding with higher depth will have velocity lower and vice versa.

In the study area there are two conditions due to inundation depth, one is the depth inside the dike and second the inundation depth because of dike broke. The inundation depth inside the dike have constant value, it range from 3 m in the edge of the dike and 8 m near of the central eruption, this information can be found on the reported maps.

The depth of inundation resulted from the dike break was found from the result of flow modeling because there were no observed information. We can found that the depth outside the dike is range from 0 to 50 cm. In stream flood such depth categorized as low hazard as showed in the Fig 7-3. below, but in this study the real condition is totally different.

Mud flow hazard has severity higher than any other hazard caused by water flood. In this case the hazard not only generated by water it self but also from concentration mud inside the mixture. Once the flood has stopped than the clay will remain and become dried and this will become serious problem for properties, health and life. Therefore the depth inundation even at 25 cm will become serious problem and create high hazard.

![Fig 7-3. The relationship depth and flow velocity with level of hazard](source:image.png)
Fig 7-4. below showed the impact of mud flow in the settlement. From this picture we can see the depth of inundation was not too high, it was about 30 to 50 cm but it start create the disaster. People can not work or live in such condition, transportation can not through it and probably the mud contain the toxic material because this mud comes up from oil and gas reservoir beneath the surface.

Fig 7-5. also showed the village which has abandoned by people because there is impossible to live and stay in that area.

7. 3. Maximum Velocity

Flood impact assessment mainly using only parameters of depth and time of duration (Chen, 2007) this because the availability of data are only depth and time duration while velocity is usually unavailable. Flow velocity is important parameter to determine the value of maximum impulse and kinetic energy in flood (Alkema, 2003). Physical damage can be determined through impulse and kinetic energy and can be also determined the level of flood hazard.
Fig 7-6. below showed the relationship the depth and flow velocity, this figure also describe the value of depth and flow velocity respect to the result on the element at risk. In this study the maximum flow velocity was only 0.5 m/s, this value is very low comparing to other flood events which have high level of flood hazard. Mud flow hazard has different characteristics, by low flow velocity and depth its still have destructive force especially because of clay concentration inside the mixture.

![Fig 7-6. Flood hazard classification based on depth and velocity](image)

**Source**: US Dept. of Land and Soil Conservation, in Tennakoon, 2004

### 7.4. Maximum Time of Duration

Time of duration is one of the important parameter in impact assessment of flood hazard, the longer time of hazard duration will cause the higher hazard and potential damage and losses. In this study the maximum time of duration is unknown because until this thesis written the hazard still occurred. From the mud flow started (29 May 2006) it has been almost two years and there is no indication that hazard will stop.

As explained in the previous section experts predicts that mud flow hazard will stop in the next 30 years, this is amazing phenomenon but almost in every place in the world mud volcanic flow will remain until years. In this case the inundation condition in that area has been controlled by dike built by government, but in several times the dike has been broke and inundated area surrounding.

Due to very long of duration time this hazard considered to be high hazard refers to graphic in Fig 7-7. In this study although the depth and velocity is small but the time duration is very long and based on this situation the mud flow hazard in this area is high.

Fig 7-8. showed the picture of settlement area at the time of 8 August 2006 which is more than one year from the hazard started. The houses are inundated in more of one year and people were moved and most of them were live in the shelter. From this condition we can found that the inundation area of mud flow hazard cannot be restore or recover, because the recovery cost in that area is very high.
Fig 7-7. The graph shows relationship between depth, kinetic energy and time of duration.

Fig 7-8. Condition of settlement area fifteen month after mud flow started.

Fig 7-9. The buildings were totally damage.
7.5. Element at Risk

Element at risk is defined as the properties, population, economic activities, services and another human activities, at risk in a certain area (Westen, Lecture note 2007). Based on this definition the calculation of element at risk is important input data in impact assessment. This parameter is not only necessary for assessing the value of potential loss and damage but also needed to designed evacuation plan, rehabilitation and reconstruction, as well as the preparedness plan before the hazard occur.

In this study the element at risk was calculated based on topographic map of 1:25.000 for derive land use information and the number of building was calculated from topographic map 1:10.000 and also using IKONOS imagery to update information about building and houses. This study of element at risk was only for physical infrastructure which can derive from topographic maps and remote sensing imagery, and another element at risk such as the population, economic activities was excluding from analysis. The study about element at risk such as population and economic activities require deep exploration on statistical parameter and field work like interviews using questionnaire. Due to lack of study time both research activities can not be done, and the condition in the field which was very delicate regarding dispute between people and gas exploration company, interview activity was impossible.

The first step to assess element at risk is to identify the type element at risk itself, in the study area the type of element at risk can be identified below:

- Building and houses
- Public facility
- Transportation facility
- Factory
- Land use
There are two type element at risk in the study area, the first is element at risk which is located inside the dike and near surrounding the dike, these element at risk were sank under mud flow. The second is element at risk which located outside the dike and can be identified through flow modeling, these element at risk was threatened by the break dike. Fig 7-10, are clearly described the element at risk.
Element at risk was determined by delineating the area inside inundated extent both inside the dike and outside the dike, then using GIS software it can be calculated based on the type of buildings or land use from topographic maps. All elements at risk were determined as totally damage, this condition is based on characteristics of mud flow itself.

Element at risk was calculated using flow modeling which simulated inundated area in 30 days. Meanwhile the element at risk inside the dike was using the inundated event at 05 January 2007. The result of calculation of element at risk can be seen below,

The result of calculation of Element at risk outside the dike (result from modeling) as follows :

Table 7-1. Element at risk outside the dike (Building type)

<table>
<thead>
<tr>
<th>No.</th>
<th>Element at Risk (Building type)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Building and houses</td>
<td>3063</td>
</tr>
<tr>
<td>2</td>
<td>Government office (village)</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Mosque</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>Moslem graveyard</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>School</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>Hospital</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Factory</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>3117</td>
</tr>
</tbody>
</table>

Table 7-2. Element at risk outside the dike (Land use type)

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT AT RISK (TYPE OF LAND USE)</th>
<th>AREA (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barren Land</td>
<td>5.565</td>
</tr>
<tr>
<td>2</td>
<td>Fish pond</td>
<td>652.167</td>
</tr>
<tr>
<td>3</td>
<td>Grassland</td>
<td>12.944</td>
</tr>
<tr>
<td>4</td>
<td>Mix Garden</td>
<td>40.555</td>
</tr>
<tr>
<td>5</td>
<td>Paddy field - Irrigated</td>
<td>187.732</td>
</tr>
<tr>
<td>6</td>
<td>Plantation</td>
<td>320.365</td>
</tr>
<tr>
<td>7</td>
<td>Shrub</td>
<td>60.254</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1279.581</td>
</tr>
</tbody>
</table>
The result of calculation of Element at risk inside the dike (result inundated event at 5 January 2007) as follows:

Table 7-3. Element at risk inside the dike (Building type)

<table>
<thead>
<tr>
<th>No.</th>
<th>Element at Risk (Building type)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Building and houses</td>
<td>1628</td>
</tr>
<tr>
<td>2</td>
<td>Government office (village)</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>Mosque</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>Moslem grave yard</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>School</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Jumlah Total</td>
<td>1673</td>
</tr>
</tbody>
</table>

Table 7-4. Element at risk inside the dike (Land use type)

<table>
<thead>
<tr>
<th>No.</th>
<th>ELEMENT AT RISK (TYPE OF LAND USE)</th>
<th>AREA (Ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Barren Land</td>
<td>134.414</td>
</tr>
<tr>
<td>2</td>
<td>Fish pond</td>
<td>3.951</td>
</tr>
<tr>
<td>3</td>
<td>Grassland</td>
<td>24.048</td>
</tr>
<tr>
<td>4</td>
<td>Mix garden</td>
<td>0.100</td>
</tr>
<tr>
<td>5</td>
<td>Paddy field - Irrigated</td>
<td>29.739</td>
</tr>
<tr>
<td>6</td>
<td>Plantation</td>
<td>190.773</td>
</tr>
<tr>
<td>7</td>
<td>Shrub</td>
<td>23.509</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>406.534</td>
</tr>
</tbody>
</table>

Table 7-5. Element at risk inside the dike (Road type)

<table>
<thead>
<tr>
<th>No.</th>
<th>Element at Risk (Road type)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Toll Road</td>
<td>4769.382</td>
</tr>
<tr>
<td>2</td>
<td>Local Road</td>
<td>4477.128</td>
</tr>
<tr>
<td>3</td>
<td>Other Road</td>
<td>38513.648</td>
</tr>
<tr>
<td>4</td>
<td>Path way</td>
<td>7142.929</td>
</tr>
<tr>
<td>5</td>
<td>Railway track- single</td>
<td>461.098</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>55364.185</td>
</tr>
<tr>
<td>Settlement</td>
<td>Toll road</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>Mud flow</td>
<td>Agricultural area</td>
<td></td>
</tr>
</tbody>
</table>

Fig 7-12. The picture of Element at risk
CHAPTER 8. CONCLUSION AND RECOMMENDATION

8.1. Conclusion

8.1.1. Conclusion from Research Objective

a. To generate and construct the mud volcanic flow model in dynamic spatial modeling environment.

This research was done successfully and the result is five flows modeling which used to analyze the flow model generated from 1D2D hydrodynamic modeling with the behavior of mud flow occurred in the study area. The inundation extent of the flow model fits 40% with the inundation extent of the mud flow hazard, but the depth of the inundation indicated only less 20% overlap between flow model and the mudflow hazard this because the model was not included the land subsidence which occurred in that area.

b. To know the propagation of the mud volcanic flows, how large the area will be affected in present and future.

The model result from SOBEK has output parameters such as inundation extent, the depth and flow velocity, this can be used to find out the area of inundation in a certain time. The simulation within period of time is constraint by a number of pixel of DTM, resolution of pixel and the timesteps, therefore there must be adjustment to set the combination of that parameters. In this study the highest computation times was 10 hours with 60 days simulation period and 178x191 number of pixel in 20 m resolution. It means the coverage area is 4 km x 4 km, for a long time simulation say it 2 years it will require higher coverage area and it will consume a lot of computation time. Therefore it is impossible to create simulation in longer time unless there is powerful supercomputer dedicated to this work.

c. To calibrate and validate the model it self, how is the reliability and accuracy of the result based on comparison with actual event.

There were several parameters with different combination values used to calibrate and validate the model, and through this step we can conclude that the surface roughness play important role to the result of the model. The surface roughness which act as resisting force in the flow of the material need to be defined as accurate as possible with the real condition in the field. The parameter like single building or building footprint was also give significant influence in the model. The building footprint as surface roughness made the area of inundation more larger and similar with the mud flow, and if the building footprint act as elevated building it will give better result. The accuracy of the model also determined by viscosity of the material and this parameter was ignored in this model.
d. To assess mud volcanic flow hazard which affected the surroundings such as settlements, buildings, roads, factory etc.
The inundation extent resulted from flow model integrate with another data such as Land use maps and Ikonos imagery, can be used to calculate element at risk for example roads, buildings, houses and land use. Another element at risk for instance the population and economic activity require further research and analysis.

8.1.2. Conclusion from Research Question
a. What types of data needed to build DEM as a platform to generate the mud flow modeling?
The DEM as a representation of relief change has to be able to capture the detail of relief change on the surface, this basic principle will require advance technique and cost. These two aspects are the major constraint for the development countries like Indonesia. Generally such data is not available. In this study topographic map scale 1:10.000 is adequate to represent the elevation data in steep slope for flow modeling. In flat terrain like in the floodplain spot height as additional elevation data to represent the relief are necessary. In this case the topographic map in scale of 1:10.000 have well distributed spot height, but there is not adequate in density, therefore additional spot height to densify the elevation is necessary.

b. How far the inundation of mud flows in the next 5, 10 and 20 years?
The computation time is major constraint to simulate flow model in longer period of time. The software will require the powerful supercomputer to process this model.

c. How reliable and accurate the model?
The reliability and accuracy the model is depend on varying parameters. The characteristics or the property of the material is one of parameters to be determined first. The behavior of flow material will be determined from this characteristic. The other parameter is roughness coefficient which is act as friction force in the flow of material, these parameters must be determined good enough in order to get optimum result.

d. How many properties and infrastructure will be affected by mud flow?
The element at risk can be identified and calculated using data of inundation extent from flow modeling. Inundation extent integrate with another GIS data can be determine the element at risk affected by mud flow. The impact assessment in chapter 7 is described this topic, and the result of element at risk calculation can be found in this chapter.
8.2. Recommendation

The study of mud flow is very important since this phenomenon is widely found in several locations in the world. This hazard is unique and has powerful energy which can put human live in great danger. Mud flow hazard if occurred in the urban area will cause the maximum loss in the properties and life. In this hazard thousand people were displaced, thirteen people were dead and thousand properties were damage or loss. For this reason the proper assessment of the hazard will safe lives and properties, by simulating the flow of the mud people and government can predict where hazard will go and able to manage the hazard in a good way.

This study of mud flow hazard probably is the beginning research since the research conducted on this field was limited especially in Indonesia. Therefore similar researches have to be encouraged in order to solve the hazard problem which can not be imagined before. The research in the social aspect of the mud flow hazard also have to be encourage so people and government can use the result to face the problem of the hazard in the future.

This study as a limited research of course has many limitation and constrains and this has to be solve in the future research. The use of proper software as main tool to simulate the hazard has to well determine as well as the understanding of the properties of mud flow. PC raster as open source software let the users to explore the capabilities of the software in the maximum limit, but it require adequate knowledge of the software itself. Therefore in the future the researcher has to provide good knowledge before use PC raster as a tool to simulate the mud flow hazard.
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