

DEVELOPMENT OF A NUMERICAL MODEL FOR
THE SIMULATION OF MUDFLOW PHENOMENON

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SCHOOL OF CIVIL ENGINEERING
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SIMULATION OF MUDFLOW PHENOMENON

By

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I hereby declare that all corrections and comments made by the supervisor(s) and examiner have been taken into consideration and rectified accordingly.

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Date :

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ABSTRAK

Pada masa kini, banjir lumpur semakin kerap berlaku disebabkan oleh kepesatan pembangunan terutamanya di kawasan bukit dan tanah tinggi. Banjir lumpur meninggalkan impak yang besar terutamanya kepada kehidupan manusia, haiwan dan juga harta benda. Salah satu faktor yang menyumbang kepada berlakunya banjir lumpur adalah penebangan hutan secara berleluasan. Kejadian banjir lumpur tidak dapat dijangka. Namun demikian, pelan mitigasi dan perancangan pembangunan yang betul dapat mengurangkan impak negatif banjir lumpur ini. Simulasi komputer dengan menggunakan model berangka merupakan antara cara yang boleh digunakan dalam membuat ramalan kejadian banjir lumpur. Dalam penyelidikan ini, satu skim berangka taraf tinggi, iaitu skim Profil Interpolasi Kubik (CIP) telah digunakan dalam model berangka tersebut. Seperti model berangka yang lain, model berangka ini telah ditentukan dengan penyelesaian beranalisis, penyelesaian berangka, dan keputusan eksperimen yang diperolehi daripada penyelidik-penyelidik terdahulu. Model berangka ini digunakan untuk mensimulasikan senario banjir lumpur setelah keputusan yang diperolehi disahkan terlebih dahulu melalui proses penentusahan. Keputusan simulasi dapat digunakan untuk memajukan rancangan pengurangan banjir lumpur dan seterusnya dapat mengurangkan impak-impak negatif banjir lumpur.

ABSTRACT

Recently, mudflow has been happening on a more frequent basis due to the rapid development especially in the mountainous and highland areas. Mudflow is known to have devastating impacts on lives and properties. One of the most probable causes of mudflow is deforestation. Mudflow is hard to be predicted but mitigation plans can be developed to reduce the negative impacts of mudflow. Numerical modelling can be a handy tool to predict the dynamics and flow extent of a mudflow disaster and therefore it can be very useful and indispensable tool to develop a sound mitigation plan. In this work, a higher order numerical scheme known as the cubic interpolation profile (CIP) was adopted in the numerical model. Like other numerical models, this numerical model was verified with analytical solution, numerical solution and experimental results obtained by past researchers. The numerical model was used to simulate mudflow scenarios after ensuring that the performance of the numerical model was satisfactory through the close agreement between the results produced by the numerical model and the data obtained from literature in the verification process. The model can be extended for practical use by incorporating geospatial data in the near future.

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CHAPTER 1

INTRODUCTION

1.1 Background

Debris flows and mud flows are the flows of water and sediments which are thoroughly mixed. The difference between debris flows and mud flows is the size of sediments. The flow with significant content of fine sediments is known as mud flow. Otherwise, it is known as debris flow (Laigle and Coussot, 1997). Hungr et al. (2014) suggested that the Plasticity Index of the material to be used as the controlling parameter. For mudflow, Plasticity Index of the material is more than 5 %. Otherwise, the flow is classified as debris flow.

In this globalized era, the use of computer has drastically changed the world in many ways especially in the field of science, technology, engineering and mathematics (STEM). In the field of fluid mechanics and hydraulics, the advancement of computers has become the catalyst for the rapid development of numerical techniques in solving complex flow problems. The technique to solve fluid flow problem with numerical method is often referred to as the Computational Fluid Dynamics (CFD).

In the past, various numerical models were developed to study fluid flow such as by using a transient one-dimensional model (Schamber and MacArthur, 1985), a two-dimensional finite difference model (O'Brien et al., 1993) and even for a non-Newtonian fluid model such as the modified Bingham numerical model (Dent and Lang, 1983). Each model has its own advantages and disadvantages compared to other models. In addition, each model is suitable for different situations. Therefore, we must choose the most suitable model for our studies in order to produce reliable results.

In this study, a numerical model is developed based on depth-averaged equations and a higher order accuracy is achieved by using the Cubic Interpolation Profile (CIP) scheme which is a third order scheme (Yabe et al., 2004).

By assuming mudflow as a continuum, the characteristics of mudflow as be approximated by several rheological models. However, for this study, Herschel-Bulkley model is used as the rheological model as it could mimic mudflow of high fines content behaviour satisfactorily (Laigle and Coussot, 1997). Previously, Chan (2016) simulated mudflow by solving the two-dimensional momentum equations with Marker and Cell (MAC) method. In addition, Chan (2016) chose Bingham model to represent the rheological properties of mudflow.

As the first step in the development of the model, the performance of the higher order scheme is investigated. The higher order scheme is then adopted in the one-dimensional and two-dimensional depth-averaged model. The one-dimensional model is verified with dam-break problem. On the other hand, the two-dimensional model is verified with partial dam-break problem. In the subsequent stage, the rheological model of mudflow is integrated in the two-dimensional model and verified against experimental data from literature study. Finally, mudflow scenarios are simulated using the two-dimensional model.

1.2 Problem Statement

There are many mudflow incidents that has occurred in Malaysia. One of them is the incident at Cameron Highlands, Pahang which happened on 22nd October 2013 at 17:00 UTC (23rd October 2013 at 01:00 Malaysian Standard Time). This incident claimed three lives as well as damaged nearly 100 houses and over 100 vehicles. It occurred after the release of water from Sultan Abu Bakar hydroelectric dam for three times. Water

must be released from the dam because the water level in the dam was reaching the danger level following the continuous rain on 22nd October 2013 at 11:00 UTC (22nd October 2013 at 19:00 Malaysian Standard Time) (Kaur et al., 2013).

On a separate incident, an earthquake with magnitude of 5.9 of Richter Scale hit Ranau, Sabah on 4th June 2015 at 23:15 UTC (5th June 2015 at 07:15 Malaysian Standard Time) (Vanar et al., 2015). About 10 days after the earthquake, mudflow and landslides hit several villages at the foothills of Mount Kinabalu. Mudflow and debris flow occurred after continuous rain since 13th June 2015. The mudflow caused water shortages, power-cuts and road damages (Chan, 2015).

In order to develop a sound mitigation plan for mudflow disaster, the understanding of the dynamics and flow behaviours is indispensable. For a complex flow problem such as the mudflow disaster, analytical solution is near impossible. Therefore, numerical modelling is crucial to analyse such flow problem and provide invaluable information for mitigation plan.



Figure 1.1: Mudflow Disaster in Cameron Highlands (Yong, 2013)



Figure 1.2: Destruction of Bridge Caused by Mudflow at Ranau (Sario and Lee, 2015)

1.3 Objectives

The objectives in carrying out this study are as follows:

1. To compare upwind and Cubic Interpolation Profile (CIP) schemes and their accuracy.
2. To develop a numerical model based on depth-averaged equations with the integration of higher order numerical scheme.
3. To verify the numerical model with numerical simulation and experiment data available from literature.
4. To simulate simple mudflow scenarios with the numerical model.

1.4 Scope of Work

In this study, a few tasks were carried out as follows:

1. Literature review

Essential for having a sufficient understanding of research topic before starting the study.

The works of other researchers in the areas related to the study are referred to and reviewed against to understand the theory behind the study.

2. Numerical modelling

A numerical model which discretizes the governing partial differential equations of fluid flow will be developed for studying the flow of the fluid. Sufficient understanding of the fluid properties is required to develop a numerical model which can reproduce the fluid properties with high accuracy.

3. Verification of numerical model

The data from the simulation with the numerical model will be compared with the simulation and experimental data obtained from available literature to determine whether the numerical model is verified.

1.5 Dissertation Outline

This section outlines the dissertation as shown below:

Chapter 1 is the introduction of the study. It gives a brief overview of the research which includes background of the study, problem statement, objectives and scope of work.

Chapter 2 is the literature review of the study. It shows the review of studies carried out by other researches which are related to this research. In addition, the properties of the fluid are also described here.

Chapter 3 describes the methodology used in this research which includes the theories and applications of the numerical model.

Chapter 4 shows the results and discussion of this study. The result from the numerical simulation of mudflow is included here. The simulation results are verified against the results from simulations and experiments by other researchers.

Chapter 5 is the conclusion and recommendations of this study. The results of this study is summarized here. In addition, recommendations for further research are also included here.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

The literature review of this study consists of six sections. Section 2.1 is the overview of the whole literature review. Section 2.2 mentions about the numerical schemes implemented in numerical models. Section 2.3 describes the rheological properties of the fluids. Section 2.4 mentions about mudflow. Section 2.5 discusses the governing equations used to develop the numerical model. Section 2.6 describes the verification of the numerical model. Section 2.7 mentions about the numerical models used in mudflow study. Section 2.8 is the summary of this chapter.

2.2 Numerical Schemes

There are many numerical schemes which are available and can be used to discretize the advection portion governing partial differential equations of fluid flow. Each scheme has its own advantages and disadvantages. Two numerical schemes will be discussed here, i.e. upwind scheme and cubic interpolation profile (CIP) scheme.

2.2.1 Upwind Scheme

According Yang et al. (2006), first order upwind scheme is stable when it satisfies Courant–Friedrichs–Lewy (CFL) condition. However, it is not able to produce accurate solutions for complex flow fields without utilizing very fine grids since it is too dissipative. According Osher and Solomon (1982), smearing occurs when first order upwind scheme is used since it diverges away from the original points. Hence, the upwind scheme is a dissipative scheme.

2.2.2 Cubic Interpolation Profile (CIP) Scheme

Takewaki et al. (1985) developed the cubic interpolation profile (CIP) scheme to solve hyperbolic equations for which the Finite Element Method (FEM) and Boundary Element Method (BEM) have not always worked with success (Takewaki et al., 1985). Yabe and Aoki (1991) developed a compact CIP method to solve general hyperbolic equations by using a spatial profile interpolated with a cubic polynomial within a grid cell. Yabe et al. (1991) developed a multidimensional compact CIP method which also utilizes a cubic spatial profile within grids to solve multidimensional hyperbolic equations without the use of time-splitting technique. Therefore, the advection term of the depth-averaged continuity and momentum equations can be solved with the multidimensional CIP method since they can be isolated into multidimensional hyperbolic equations. A universal solver for hyperbolic equations used for compressible and incompressible fluid was successfully developed by Yabe (1991) which uses CIP scheme to solve the advection term in the governing equations.

2.3 Rheological Properties

According to Steffe (1996), the word ‘rheology’ was first used by Eugene C. Bingham (1928). It is known as the science of the deformation and flow of matter. It is the study of the response of materials to applied stress or strain. The rheological properties of Newtonian fluids and Non-Newtonian fluids will be briefly discussed here. The constitutive relations of Newtonian fluids and Non-Newtonian fluids will also be discussed here.

2.3.1 Newtonian Fluid

A Newtonian fluid is a fluid in which the shear stress, τ is directly proportional to shear rate, $\partial u/\partial y$ (Eq. 2.1). The constant of proportionality is known as dynamic viscosity, μ – ‘Rheological Characterization’ (Björn et al., 2012, p. 64).

$$\tau = \mu \frac{\partial u}{\partial y} \quad (2.1)$$

2.3.2 Non-Newtonian Fluid

A Non-Newtonian fluid is a fluid in which the relationship between shear stress, τ and shear rate, $\partial u/\partial y$ cannot be described by Eq. 2.1. The dynamic viscosity, μ is not constant with respect to shear rate as it may increase or decrease with shear rate. Figure 2.1 and 2.2 compare the behaviour of Newtonian fluids and some Non-Newtonian fluids.

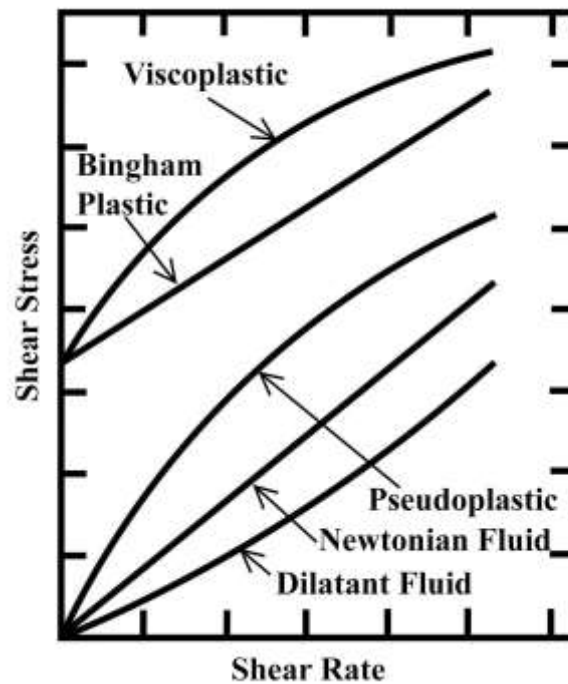


Figure 2.1: Graph of Shear Stress versus Shear Rate for Newtonian and Various Non-Newtonian Fluids (Chhabra, 2010)

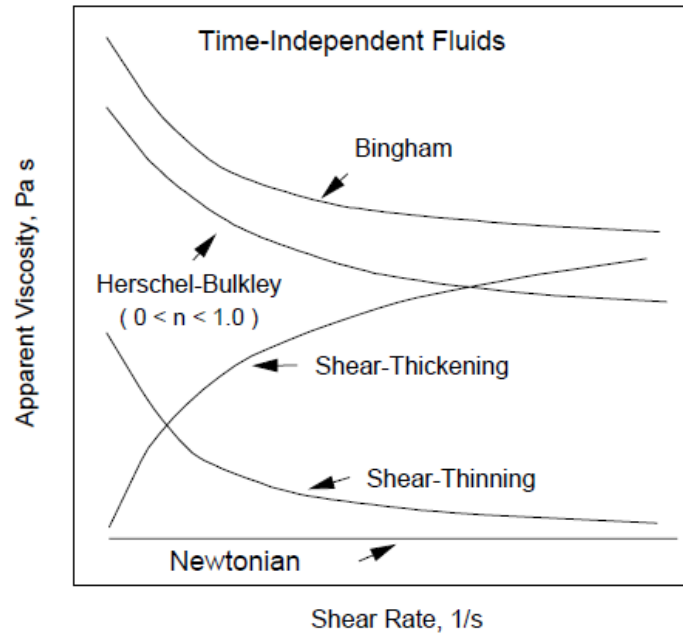


Figure 2.2: Graph of Apparent Viscosity versus Shear Rate for Newtonian and Various Non-Newtonian Fluids (Steffe, 1996)

2.3.3 Constitutive Relations

According to Steffe (1996), constitutive relations are the equations which describes the relationship between stress and strain. These equations may include other variables such as time, temperature and pressure in the case of complex materials. Constitutive relations differentiate various fluid models, especially Non-Newtonian fluids from one another.

2.3.3.1. Newtonian Fluid

According to Currie (2003), the constitutive relation for stress in a Newtonian fluid is shown in Eq. 2.2: