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Viscosity Determination of Soil in Plastic and Viscous Liquid States for Elucidating Mudflow Behavior

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Viscosity Determination of Soil in Plastic and Viscous Liquid States for Elucidating Mudflow Behavior

Budijanto Widjaja

National Taiwan University of Science and Technology, 2012

Advisor: Prof. Shannon Hsien-Heng Lee

ABSTRACT

The transformation of soil from a plastic state into a viscous liquid state is primarily caused by changing the water content of the soil mass. As the water content increases, the soil mass gradually starts to behave like a viscous liquid. In spite of viscosity being a key parameter to the behavior of mudflows, there have no datasets of soil viscosity changes successfully measured continuously as they move from plastic to viscous liquid states. The aim of the current research is to design a new device to overcome this difficulty. Based on the trap door principle formulated by Terzaghi (1943) and the Bingham model, a new device called the Flow Box was designed. The governing equation of the Flow Box was derived in this research in order to obtain the relationship between initial viscosity and liquidity index. In this study, the viscosities in both plastic and viscous liquid states were clearly defined by the Flow Box Test. The expected decrease in initial viscosity was followed by an increase in liquidity index, which corroborated with the test results. The initial viscosity readings with the results of other similar research and the case study of the Maokong mudflow was also validated.

Hence, the purpose of this research to create a new device to successfully determine viscosity levels as soil changes from plastic to liquid state is completed.

The phase concept implies that the state of soil changes from plastic to viscous liquid as a function of water content. This principle could be used to interpret the behavior of mudflow, which is the most dangerous mass movement today. When Typhoon Jangmi hit northern Taiwan in 2008, a mudflow occurred in the Maokong area as the result of a high-intensity rainfall. This case was studied using three scenario simulations each with different water contents. Based on the mudflow classifications, the primary criteria used were flow velocity and solid concentration by volume. The results show that the mass movement confirms the aforementioned criteria for mudflow especially when the water content reaches or exceeds the liquid limit. The validation using Karanganyar and Ciwidey mudflows has the similar trend to Maokong mudflow. The flow box test can determine the viscosity for both plastic and viscous liquid states, which is advantageous. Viscosity is important in explaining the general characteristics of mudflow movement because it controls flow velocity. Therefore, the present study successfully elucidates the changes in mudflow from its transportation to its deposition via numerical simulation using laboratory rheology parameters.

Keywords: mudflow, viscosity, water content, liquid limit, liquidity index, rheology.

塑性和黏滯液性土壤之黏滯性檢測及其應於土石流行為解析

博士候選人： 倪金安

指導教授： 李咸亨

摘要

含水量是促使土壤由塑性體轉變成黏滯性液體的主要原因，含水量增加後，土壤行為就逐漸像黏滯性液體一樣。雖然黏性值(viscosity)是如此重要的關鍵因子，卻只有少數資料曾經成功地量測到土壤由塑性體轉變成黏滯性液體時的所有過程中黏性值，本研究的目標就是希望設計一個能夠克服此難題的新儀器。

根據 Terzaghi (1943)的活板門原理(trap door principle)和 Bingham 理論，本研究設計了一個新儀器-流速盒，也推導出該流速盒之控制方程式，以計算黏性值與液性指標之關係。研究中，土壤由塑性體轉變成黏滯性液體時的每一過程，新儀器(流速盒)都成功地量測到黏性值。當液性指標增加時，黏性初值就減少。流速盒量測之黏性初值和其他研究資料相符，也能驗證貓空土石流行為。因此，新儀器達成目標了。

相位理論(The phase concept)蘊含著含水量是促使土壤由塑性體轉變成黏滯性液體的因子，可用以解釋危險的土石流行為。本研究以三種不同含水量模擬2008 年薔蜜颱風襲擊北台灣時，大雨造成的貓空土石流。流速(flow velocity) 和固體之體積濃度(solid concentration by volume)是主要的流變學參數，被用於土石流

分類規範。新儀器(流速盒)直接量測降伏應力和黏性初值。研究結果顯示含水量達到或超越液性限度時，貓空土石流堆積量預測值和現場一致。另外，印尼的 Karanganyar 和 Ciwidey 地點的兩個案例也有成功的結果。

流速盒的優點是能夠直接量測土壤由塑性體轉變成黏滯性液體時每一階段之黏性值，而黏性值主導液體土壤之流速，也用於解釋土石流行動。因此，本研究以流速盒獲得的流變學參數進行數值模擬分析，並成功地解釋土石流由流動區至堆積區的現象。

關心詞：土石流，黏性值，含水量，液性限度，液性指數，流變學。

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DEDICATION

Specially dedicated to my family: Amel and Caca for all their love.

For in Him all things were created: things in heaven and on earth, visible and invisible, whether thrones or powers or rulers or authorities; all things have been created through Him and for Him. (Colossians 1:16)

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LIST OF SYMBOLS AND NOMENCLATURE

English Letters-Upper Case

A	Surface/flow area or area perpendicular to vertical force	$[L^2]$
A_s	External specific surface area of clay grains	$[L^2]$
B	Width	[L]
C_1	Constant for FBT	$[L^{-1}]$
C_2	Constant for FBT	
CL	Clay with low plasticity	
C_v	Solid concentration by volume	
D_{50}	diameter of particle related to 50% finer	[L]
DST	Direct ShearTtest	
FBT	Flow Box Test	
F_B	Buoyancy force	[F]
F_v	Overburden pressure	$[FL^{-2}]$
F_f	Friction along the failure surface	$[FL^{-2}]$
G_s	Specific gravity	
H	Height of sample/box	[L]
HSM	Hyperconcentrated Sediment Mixtures	

K	Consistent coefficient (for Herschel Bulkley model)	
K	Resistivity parameter for laminar flow	
K_a	Active earth pressure coefficient	
L	Length of sample	[L]
L'	Flow length	[L]
LL	Liquid limit	
LI	Liquidity index	
LVDT	Linear variable differential transformer	
MBT	Moving ball test	
ML	Silt with low plasticity	
MH	Silt with high plasticity	
P	Perimeter	[L]
PL	Plastic limit	
Q	Discharge	$[L^3T^{-1}]$
R	Flow area divided by the flow perimeter	[L]
S_f	Final saturation	(%)
S_{fx}	Friction slope component	
S_i	Initial saturation	(%)

S_{ox}	Slope of the bed	
SR-5	Stress Rheometer	
T	Temperature	(deg.)
T	pull-out force for Moving Ball Test	[F]
USCS	Unified Soil Classification System	
V_{solid}	Volume of the solid part	[L^3]
V_{water}	Volume of the pore water	[L^3]
W	Weight of slice (FBT) or weight of sphere (MBT)	[F]

English Letters-Lower Case

c	Cohesion	[FL^{-2}]
c_{min}	Minimum cohesion	[FL^{-2}]
d	Displacement	[L]
d_o	Immediate displacement	[L]
dv	Change of velocity	[LT^{-1}]
dx	Displacement in x-direction	[L]
dy	Displacement in y-direction	[L]
$d\gamma$	Change in shear strain	
dz	Thickness of slices	[L]

dv/dy	Shear strain rate	[T^{-1}]
e	Void ratio	
k	Soil permeability	[LT^{-1}]
k	Spring constant	[FL^{-1}]
k_r	Rainfall intensity	[LT^{-1}]
h	Wetting front depth	[L]
h	Flow depth	[L]
g	Gravity acceleration	[LT^{-2}]
h_f	Flow depth related to friction slope component	[L]
n	Porosity	
n	Flow index for Herchel-Bulkley model	
n	Manning's coefficient	
q	Distributed/additional loading	[FL^{-2}]
r	Radius of sphere	[L]
v	Velocity	[LT^{-1}]
t	Time	[T]
t	Rainfall duration	[T]
t	Thickness of adsorbed water on the external clay surface	[L]

t_{opt}	Optimum time	[T]
w	Water content	[%]
w_{ea}	Quantity of adsorbed water on the clay surface	[%]
w_{ep}	Quantity of free pore water	[%]
w_i	Amount of inter-layer water	[%]
v_x	Average velocity in x-direction	[LT^{-1}]
z	Depth	[L]

Greek Letters-Upper Case

ΔF_v	Increasing of overburden pressure	[FT^{-2}]
Δx	Displacement in x-direction	[L]

Greek Letters-Lower Case

γ	Unit weight	[FL^{-3}]
γ	Shear strain	
$\dot{\gamma}$	Shear strain rate	[T^{-1}]
δ	Field constants determined by laboratory tests	
ε	Axial strain	[%]
η	Viscosity	[$FL^{-2}T$]

η_a	Apparent viscosity	$[FL^{-2}T]$
η_B	Bingham's viscosity	$[FL^{-2}T]$
η_K	Schwedoff's viscosity	$[FL^{-2}T]$
θ	Angle caused by shear stress	(deg.)
ν	Kinematic viscosity	$[L^2T^{-1}]$
σ'	Effective stress	$[FL^{-2}]$
σ_v	Vertical total stress	$[FL^{-2}]$
τ	Shear stress	$[FL^{-2}]$
τ_y	Yield stress	$[FL^{-2}]$
τ_{yB}	Bingham's yield stress	$[FL^{-2}]$
τ_{yK}	Schwedoff's yield stress	$[FL^{-2}]$
τ_{yx}	Shear stress in x-y space	$[FL^{-2}]$
ϕ	Internal frictional angle	(deg.)

Chapter I

INTRODUCTION

1.1 BACKGROUND

Mudflow is a very rapid flow-like movement of saturated, fine-grained mass of material with water content equal to or higher than the liquid limit (LL). Mudflow can be considered one of the most dangerous types of mass movement because of their sudden occurrence (Michael, 2009). Hence, research on its complex characteristics during its initiation, transportation, and deposition is important. When soils change from solid phase to plastic phase, the shape of the soil mass becomes gradually deformed. When water content increases to the liquid limit level, the mass of soil starts to move very quickly, like a liquid. In this condition, the soils are defined to be in the viscous liquid phase and move like mudflow (Lee and Widjaja, 2011).

Several factors, including high intensity rainfall and infiltration on a steep slope (20° – 45°), trigger mudflow (Hungr et al., 2001). Predicting the consequences of these factors is difficult because the triggering factors are functions of the weather (Vaughan, 1994). Therefore, predicting mudflow as a geomorphic hazard is probably even more difficult than forecasting the weather.

By definition, mudflow is initiated when water content (w) is equal to or higher than liquid limit (LL). However, the viscosity (η) of a soil is difficult to determine because of the limitations of the conventional viscometer. A viscometer is designed to take measurements when the liquidity index (LI) of the viscous liquid is greater than one (Blight, 1997; Dinger, 2005; Blight, 2010). However, the value of η varies according to the level of shear strain rate and type of viscometer. Therefore, η is an important parameter that is not easily determined. Currently, the author has not found any commercial apparatus that could be used to measure the viscosity of material in conditions very close to LL.

To date, direct laboratory tests on the liquid limit (LL) and their direct simulations have not yet been conducted. In this research, the author conducted the direct shear test (DST) and moving ball test (MBT) by Lee et al. (2008) and Hendriks (2009), respectively to obtain yield stress (τ_y), which is the key mudflow parameter for the numerical simulation. Since viscosity is an important parameter in elucidating the triggering factors related to the behavior of mudflow, the present study aims to develop a new laboratory model for clay samples based on the trap-door principle (Terzaghi, 1943) called the "Flow Box". The Flow Box Test (FBT) offers the advantage of measuring viscosity (η) in both plastic and viscous liquid states using displacement data.

1.2 PROBLEM STATEMENT

The viscosity (η) values determined by other researchers range from 7.6 mPa•s to 500,000 Pa•s, as seen in Fig. 1. 1. Locat and Demers (1988), Locat (1997), and Jeong (2010) used a rotational viscometer to study submarine mudflow samples. They showed that, for submarine mudflow of materials in the viscous liquid state, the relationship between viscosity and liquidity index is nearly linear. Researchers have also examined kaolin mudflow with MBT (Lin, 2008), SR-5, both MBT and SR-5 in combination (Lee et al., 2008), a laboratory flume channel (Vallejo and Scovacco, 2003), and a fall cone penetrometer (Mahajan and Budhu, 2006; Mahajan and Budhu, 2008). These studies show that the minimum viscosity is 7.6 mPa•s (Locat and Demers, 1988). Most researchers use a viscometer to obtain viscosity, but unfortunately, viscometer results are valid only for material in the viscous liquid state (Dinger, 2002).

Different types of tests have been developed to determine viscosity. An initial approach was to simulate the viscous drag on shafts during pile penetration for the plastic state (Mahajan and Budhu, 2006). More recently, viscous drag has been simulated using the fall cone penetrometer coupled with the Bingham model (Mahajan and Budhu, 2008). The latter extended their research and found that the trend is linear in both plastic and viscous liquid states as seen in Fig. 1. 1. Vallejo and Scovacco (2003) measured the difference in velocity between two points using the Bingham theory. In those three studies, relatively high viscosities were shown in the range between 30 Pa•s - 500,000 Pa•s. However, those results from the viscous drag on shafts during pile penetration could not possibly be used to explain the behavior of mudflow on a natural slope.

1.3 OBJECTIVES

This research began with the development of the governing equation of flow box test (FBT) and an apparatus to measure initial viscosity as a function of liquidity index (LI). To verify the results, the method was applied to kaolin soil as a pilot project and soil samples from three actual mudflow cases. The proposed method is called "phase concept". The cases are Maokong, Karanganyar, and Ciwidey mudflows. Comparisons were then made with previous research results.

More research into the viscosity of materials in the plastic and the viscous liquid states are needed to provide reliable understanding of the behavior of mudflows. The purpose of this research was to develop and validate the Flow Box Test in order to derive the relationship between initial viscosity and liquidity index. The measured initial viscosity was then validated against results from other research.

Subsequently, back analysis of the Maokong mudflow case study was conducted to determine the accuracy of the prediction using measurement results. Then, the other objective of this study was to simulate the Maokong mudflow using three different water contents (*w*) comparing to its liquid limit (LL) by using the measured parameters from Flow Box Test (FBT). These processes are based on the rheology parameters derived from the FBT. The three scenarios were: (i) plastic state (w<LL), (ii) liquid limit (w=LL), and (iii) viscous liquid state (w>LL). The behavior of each state (i.e., flow depth, flow velocity) was analyzed and categorized (i.e., landslide or mudflow). The numerical simulation was then compared to the actual mudflow event. Then, validation using Karanganyar and Ciwidey mudflow was applied using the same procedure for Maokong mudflow.

Hence, the purpose of this research was to elucidate the mudflow process from its transportation to its deposition by varying the water content levels and applying the FBT results.

1.3.1 Research hyphotesis

Other researchers (Vallejo and Scovazzo, 2003; Mahajan and Budhu, 2006; Mahajan and Budhu, 2008) have developed alternative means, such as the flume channel and fall cone penetrometer, to obtain viscosity measurements of materials in different states. Mahajan and Budhu (2008) derived a linear relationship between viscosity (η) and liquidity index (LI) in both plastic and viscous liquid states. However, those results gave unreasonably high values for the initial viscosity, which are unable to explain the behavior of mudflows in actual cases. This study discusses the abovementioned issues and subsequently presents the design and testing of the new "Flow Box" device.

The hypothesis for this research is as follows: the relationship of viscosity and LI is not linear for a material transitioning from the plastic to the viscous liquid state. Viscosity is thus a key parameter in explaining the behavior of mudflow due to changes in soil conditions.

1.3.2 Research limitation

The main aim of this research is to develop a new laboratory device so called Flow Box Test (FBT) related to the research about mudflow. This test provides the relationship between viscosity and liquidity index based on the Bingham's model. Therefore, the result is limited for describing the behavior of mudflow (i.e., its transportation to its deposition) using FBT result based on the change of water content and viscosity. The change of water content is divided into two states: plastic and viscous liquid states. Hence, this result does not include landslide initiation caused by rainfall.

1.4 OVERVIEW OF THE PROPOSED METHOD

Since viscosity is an important parameter in elucidating the triggering factors related to the behavior of mudflow, the present study aims to develop a new laboratory model for clay samples based on the trap-door principle (Terzaghi, 1943) called the "Flow Box". The Flow Box Test (FBT) offers the advantage of measuring viscosity (η) in both plastic and viscous liquid states using displacement data.

Some researchers (Varnes, 1978; Cruden and Varnes, 1996; Hungr et al., 2001) believe that mudflows are closely related to Atterberg limits, liquidity index (LI), and flow velocity (v). Hence, from the time of mudflow initiation to its actual movement, the soil mass could change rapidly from a plastic to a viscous liquid state. However, some important initiating factors of mudflows (e.g. water content, time, and loading) are still inadequately explained due to deficiencies in current conventional laboratory tests, such as measurements taken from viscometer readings. The viscometer is limited to measuring the viscosity (η) of only viscous liquids and not that of materials in the plastic state.

Since phase concept indicates the change in both plastic and liquid states as a function of water content (w), the viscosity (η) could be reliably calculated from the derived flow curves. In this research, the use of the viscosity (η) data and yield stress (τ_y) data obtained with these devices is demonstrated to interpret the actual Maokong, Karanganyar and Ciwidey mudflow cases using a numerical simulation. Back analysis using published empirical rheology parameters based on the deposition area has also been employed (Sosio et al., 2007; d'Agostino and Tecca, 2006; Calligaris et al., 2008).

1.5 ORGANIZATION OF THE DISSERTATION AND SIGNIFICANT CONTRIBUTION

This dissertation presents to study the behavior of mudflow through interpretation using new laboratory device so called Flow Box Test and numerical simulation result using the real mudflow cases. It is organized in five different chapters in which Chapter 1 is introductory one, which gives the general to specific problems and approach that was supposed to follow to complete the research work.

Chapter 2 is mainly discussed about the literatures and state of the art of mudflow research. This chapter discusses the definition of mudflow which its behavior is governed by water content using rheology model. The previous research such as Moving Ball Test is discussed.

Chapter 3 deals with the development of governing equation of Flow Box Test using the couple of trap door concept and Bingham's model. Then, the result and detailed discussion through parametric study of Flow Box Test and the software FLO2D are presented include the general characteristics of mudflow behavior.

Chapter 4 describes the proposed numerical result using Maokong mudflow case by applying the laboratory result from Flow Box Test. Then, validation using both Karanganyar and Ciwidey mudflow is compared to Maokong mudflow.

Chapter 5 presents a summary of the conclusions drawn from the dissertation's work. Furthermore, a list of recommendations for future work in this area is included. The overall scope, objectives, methodologies and corresponding chapters of this dissertation are summarized in Fig 1.2.