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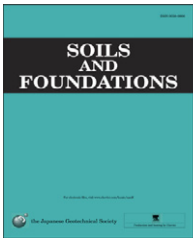

# Flow box test for viscosity of soil in plastic and viscous liquid states

Budijanto Widjaja[1], Shannon Hsien-Heng Lee*

*Department of Construction Engineering, National Taiwan University of Science and Technology, No. 43 Keelung Road, Section 4, Taipei 106, Taiwan, ROC*

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**Abstract**

The transformation of soil from a plastic state to a viscous liquid state is primarily caused by a change in 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 initiation of mudflows, there have only been a few datasets on soil viscosity changes successfully measured continuously as the soil moves from a plastic state to a viscous liquid state. The aim of the current research is to design a new device to overcome this problem. 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 the initial viscosity and the 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 the liquidity index, which corroborated with the test results. The initial viscosity readings were also validated with the results of other similar researches and the case study of the Maokong mudflow. Hence, the purpose of this research is to create a new device to successfully determine the viscosity levels as soil changes from the plastic state to the liquid state.

*Keywords:* Mudflow; Viscosity; Liquid limit; Liquidity index; Rheology (IGC: E6)

## 1. Introduction

Since viscosity is an important parameter in elucidating the triggering factors related to the initiation of mudflows, 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 ($\eta$) 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, the liquidity index (LI), and the flow velocity ($v$). Hence, from the initiation of a mudflow to its actual movement, the soil mass could change rapidly from a plastic state to a viscous liquid state. However, some important initiating factors for mudflows (e.g., water content, time, and loading) remain 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 ($\eta$) of only viscous liquids and not that of materials in the plastic state.

Other researchers (Vallejo and Scovazzo, 2003; Mahajan and Budhu, 2006, 2008) have developed alternative means,

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*Corresponding author. Tel.: +886911663909.
*E-mail addresses:* geotek.gw@gmail.com (B. Widjaja), leeshh@mail.ntust.edu.tw, leeshh39@gmail.com (S. Hsien-Heng Lee).
[1] Tel.: +886970904203.

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such as the flume channel and the fall cone penetrometer, to obtain viscosity measurements of materials in different states. Mahajan and Budhu (2008) derived a linear relationship between $\eta$ and LI in both plastic and viscous liquid states. However, the results gave unreasonably high values for the initial viscosity, which are unable to explain the initiation of mudflows in actual cases. This paper discusses the abovementioned issues and subsequently presents the design and the 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 state to the viscous liquid state. Thus, viscosity is a key parameter in explaining the initiation of mudflows due to changes in the soil conditions.

## 2. Background

### 2.1. Rheology

Rheology is a constitutive law that dictates the behavior of flows (Vyalov, 1986; Lorenzini and Mazza, 2004). Currently, both Newtonian and non-Newtonian models are in use. Non-Newtonian fluids, as modeled in [Fig. 1(a)], are dependent on two rheological parameters, namely, the yield stress ($\tau_y$) and the viscosity ($\eta$), whereas Newtonian fluids only use parameter $\eta$. Values for both $\tau_y$ and $\eta$ can be obtained with a viscometer. If the mobilized shear stress ($\tau$) is lower than $\tau_y$, then the soil is in a plastic state. Otherwise, the soil is in a viscous liquid state (Krizek, 2004). Non-Newtonian fluids are considered as time-dependent or time-independent problems related to temperature ($T$) and shear strain rate ($\dot{\gamma}$).

Some researchers treat mudflows as viscous liquids with a non-Newtonian model (Lorenzini and Mazza, 2004). In this research, mudflows are considered as non-Newtonian, time-dependent problems with a high shear strain rate level and a constant temperature.

### 2.2. Yield stress and viscosity

Fig. 1(a) shows a nonlinear curve for real mudflow behavior in the $\tau_y$ and $\dot{\gamma}$ plane (Mikhailov and Rebinder, 1955). The $\tau_y$ parameter indicates the minimal shear stress required to cause motion. O'Brien and Julien (1988) stated that $\tau_y$ is similar to cohesion ($c$). The value for $\tau_y$ can be derived from viscometry data having similar or different $\eta$ (Ferraris and Winpigler, 2000), which implies that $\tau_y$ is constant for a particular water content ($w$).

Viscosity ($\eta$) describes fluid stiffness and measures the resistivity of a fluid to flow. The gradient line at a particular point in Fig. 1(a) is $\eta$. Therefore, $\eta$ is defined as the shear stress required for a fluid to pass from one layer to another for a specific distance away from the original position of the fluid with unit velocity (Douglas, 1975). Lee et al. (2008) developed the moving ball test (MBT), which is a pulling-sphere type of viscometer based on the Navier–Stokes equation. The MBT results agree well with the results of the Stress Rheometer (SR-5), which is a popular, commercial, torque-type of viscometer.

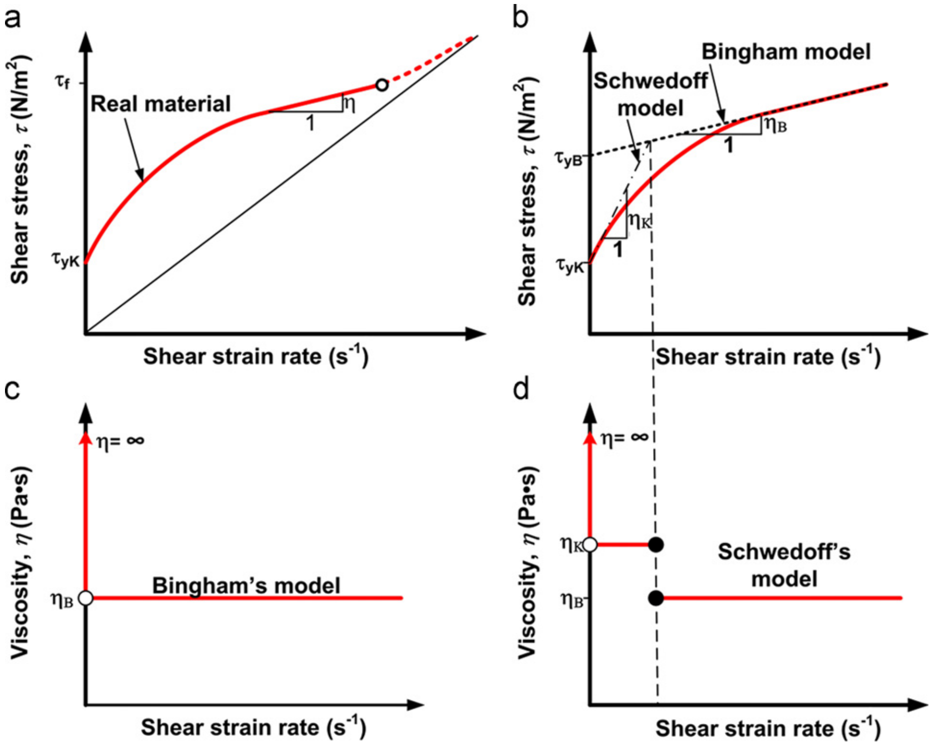

Fig. 1. Behavior of mudflow with (a) model for real material, (b) Schwedoff and Bingham model, (c) viscosity behavior of Bingham model, and (d) viscosity behavior of Schwedoff model.