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DETERMINATION OF THE VISCOSITY VALUE BASED ON THE INFLUENCE OF THE SLIDING PLANE BY USING A FLUME CHANNEL

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ABSTRACT

Mudflow is a type of mass movement with high velocity. It is comprised mainly of silt and clay-sized particles. Mudflow movement behavior involves undrained shear strength and viscosity as part of a resistance force that withstands shear stress as a driving force. Many methods have been developed to determine the value of viscosity. This study used Vallejo and Scovazzo's modification method to determine the viscosity value, and assumed that mudflow material behaves as a Bingham plastic material. A flume channel was used in this study to measure the displacement and time required for mud to flow in order to obtain the mudflow transportation velocity. The measurement was conducted for four different slope angles and water contents. To compare the samples, Kaolin soil was used for the pilot project and Parakan Muncang soil was used as the natural landslide material in order to obtain the viscosity value throughout this study. This study aims to evaluate the capability of Vallejo and Scovazzo's method to determine the viscosity value. We found that Vallejo and Scovazzo's method cannot be used in a single slope angle. This approach requires that the sliding plane angle be adjusted for varying shear stress magnitudes, and that, consequently, different strain rates for each shear stress are obtained. The correlation curve between the shear stress and the strain rate, which corresponds to the Bingham plastic material curve, needs to be governed. The viscosity value was obtained by calculating the gradient of the linear tangent line. Furthermore, Vallejo and Scovazzo's method is recommended only for tests at a low strain rate level, as a high strain level would cause difficulties in recording string displacement and mud transportation time. However, testing mud at a low strain rate level will obtain a higher value of mud viscosity that is not representative of mudflow viscosity.

Keywords: Liquid limit; Mudflow; Undrained shear strength; Viscosity; Water content

1. INTRODUCTION

Mudflow is a type of mass movement that consists of more than 50% silt and clay-sized particles, and that has a water content equal to or higher than its liquid limit (Jeong, 2010; Lee & Widjaja, 2013; Widjaja & Lee, 2013). The viscosity (η) parameter and undrained shear strength (c_u) affect mudflow movement in resisting the shear stress (τ) force due to gravity force. Mudflow movement behavior can be expressed as follows:

$$\tau = c_u + \eta(dv/dy) \tag{1}$$

where (dv/dy) is the strain rate or the velocity gradient of the mudflow.

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Equation 1 shows that the mudflow behaves as a Bingham plastic material. The Bingham plastic material model is used to simulate mudflow behavior by using linear relationships at high strain rate levels.

The viscosity and undrained shear strength are two parameters that need to be determined in order to understand mudflow behavior. When the shear stress exceeds the undrained shear strength of mud, viscosity takes over to indirectly resist the shear stress, and mud begins to flow. Thus, viscosity is a value that expresses the resistance of fluid to flow. Viscosity is an important parameter. Due to the limitations of the conventional viscometer, it is difficult to determine viscosity when the water content condition is very close to the liquid limit (LL) (Lee & Widjaja, 2013). Several researchers have attempted to obtain viscosity value by different methods, such as that proposed by Vallejo and Scovazzo (2003), which uses a flume channel instrument. This study uses the method of Vallejo and Scovazzo (2003) with some modifications in order to determine the viscosity parameters of kaolin and Parakan Muncang soils and to evaluate whether the viscosity value obtained by this method is higher than other recent viscosity research results.

2. EXPERIMENTAL

Vallejo and Scovazzo's method involves a laboratory-based experiment to determine the viscosity of mudflow (Vallejo & Scovazzo, 2003). This method also uses a channel with strings that attach inside to measure the flow velocity of mud, and the viscosity was calculated by using an equation. The following modified equation shows the authors' evaluation of Vallejo and Scovazzo's (2003) equation for the determination of the viscosity of mudflow:

$$\eta = \frac{\gamma_f h^2 \sin\beta - 2c_u h}{2(V_t - V_b)} \tag{2}$$

where η is viscosity (Pa•s), γ_f is the unit weight of mud (kN/m^3), h is the sample height (m), β is the slope of the sliding plane, c_u is the undrained shear strength of mud (kN/m^2), V_t is the velocity at the top of the mud sample (m/s), and V_b is the velocity at the bottom of the mud sample, which contacts with the sliding plane (m/s). The sliding plane is the surface area where the driving and resisting shear force occurs in the soil mass movement mechanism, represented as a planar surface. This sliding plane is then represented by the slope angle of the planar surface. As shown in Figures 1 and 2, the sliding plane is located at the bottom part of the channel. The authors' evaluation of the undrained shear strength in Equation 2 is two times higher than that of Vallejo and Scovazzo's (2003) original equation.

The flume channel used in this experiment is made of Plexiglas® that has the same dimensions as Vallejo and Scovazzo's (2003) instrument (80 cm in length, 15 cm in height, and 20 cm in width). In this study, a number of modifications were made to the instrument and method used by Vallejo and Scovazzo (2003). The original device uses only two strings behind the gate of the channel that contains the mud sample to measure the displacement during the test (Figure 1). Our proposed experiment used 14 strings that are attached from edge to edge of the channel every 5 cm (Figure 2) to record the displacement along the channel during the test duration. The mud transportation time is also recorded to calculate the average flow velocity of the mud sample. The average flow velocity is then input in Equation 2, together with the mud sample unit weight, undrained shear strength, sample height, and slope angle, in order to obtain the mud sample viscosity as the output.

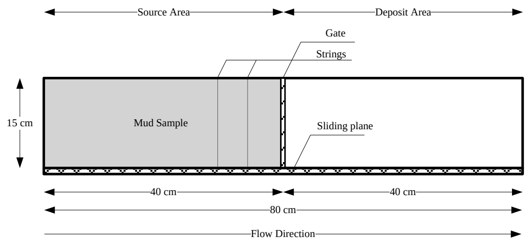


Figure 1 Instrument of the original flume by Vallejo and Scovazzo (2003)

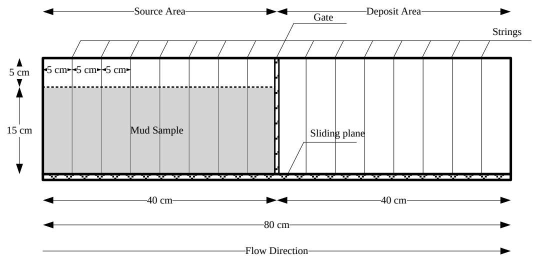


Figure 2 Modification of Vallejo and Scovazzo’s (2003) instrument

Kaolin and Parakan Muncang soils were used in this study. According to the unified soil classification system, ParakanMuncang soil is classified as clay with high plasticity (CH), and kaolin is classified as silt with high plasticity (MH). Their basic soil properties are shown in Table 1, in which *LL* refers to liquid limit, *PL* refers to plastic limit, *PI* refers to plasticity index, and G_s refers to specific gravity. The soil classification for the sample indicates that the soil samples were dominated by fine-grained soil. Furthermore, Parakan Muncang soil has a higher percentage of silt and clay material (85.74%) than kaolin soil (75.53%), as shown in Figure 3.

Table 1 Soil sample properties

Sample	*PL*	*LL*	*PI*	G_s	Soil Classification
Kaolin	38.00	68.00	30.00	2.61	MH
Parakan Muncang	29.28	66.64	37.36	2.60	CH

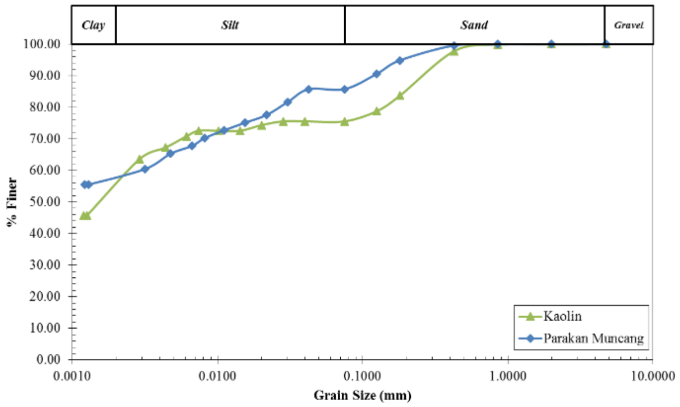


Figure 3 Grain size distribution curve for Kaolin and Parakan Muncang

Vallejo and Scovazzo (2003) used kaolin as a mud model, and performed tests at a single angle 39° from the horizontal axis. In the present study, two types of soil, namely, kaolin and Parakan Muncang, are used as the soil samples in the flume channel. Kaolin is used for the pilot project, and Parakan Muncang soil is then used for verification. The latter was collected from the landslide deposit area at the Parakan Muncang region, West Java, Indonesia.

The experiment was begun by preparing a sample with the desired water content. The volume of the soil was approximately 12,000 cm^3. This experiment used four different water contents (w). The w for the kaolin soil and Parakan Muncang soil ranged from 68.00% (equal to LL) to 88.40% (1.3 LL), and from 86.63% (1.3 LL) to 106.62% (1.6 LL), respectively. The initial water content was related to certain water content conditions, wherein the sample began to move at a certain slope angle. The initial water content was determined by making the value of w equal to LL, and performing tests from an initial slope angle of between 15°–25°, depending on the soil sample, until the maximum angle (40°) was reached by adding 5° for each trial. This range of the slope angle reflects real mudflow steepness in the field (Liu & Mason, 2009; Schrott et al., 1996). Once the initial water content was obtained, the desired water content was determined by adding $0.1LL$ until four variations of the water content were reached.

The test was begun with the desired water content value at a certain slope angle, at which the sample starts to move precisely. In this study, the slope angles used for the Parakan Muncang soil began at 25°, and that for the kaolin soil began at 15° or 25°. The test criterion was that the mud sample behind the gate was not allowed to move through the upper side of the gate before the gate was opened. Then, the initial angle was added with 5° in the succeeding test. The test was conducted with four different slope angles, but was terminated if the test criterion was not satisfied. The transportation time was measured as the duration from the opening of the gate until the final deposition of the mud. At the same water content or liquidity index, different shear strain rates were obtained at different shear stresses. The shear stress–strain rate variation was plotted on a shear stress–strain rate curve (the shear stress is the vertical axis and the strain rate is the horizontal axis) for Bingham plastic material analysis (Locat & Demers, 1988; Locat, 1997). The viscosity parameter (η) was obtained from the gradient of the linear line that coincides with the shear stress–strain rate curve at the end of the curve (Figure 4), and the yield stress of the mud was obtained from the intersection of the linear line with the vertical axis.

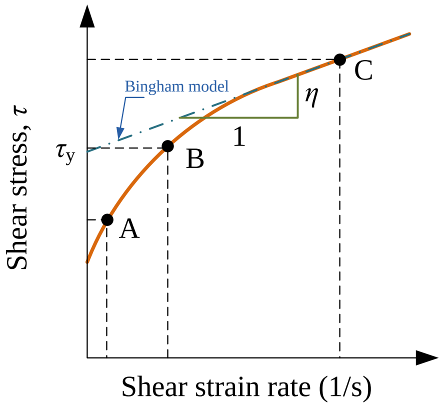


Figure 4 Determination of viscosity using the Bingham model

Figure 4 shows the Bingham plastic model curve for obtaining the viscosity value for mudflow. In the Bingham model, mudflow viscosity is represented by point C, at which the shear stress and strain rate data are higher than the others (points A and B). The viscosity value is represented with a gradient of the linear line of the Bingham model (dash-dot line), which coincides with point C. The tangent line (i.e., the gradient line) that coincides with either point

A or point B will generate a higher gradient than point C. Thus, point A or point B will generate a higher viscosity value than point C.

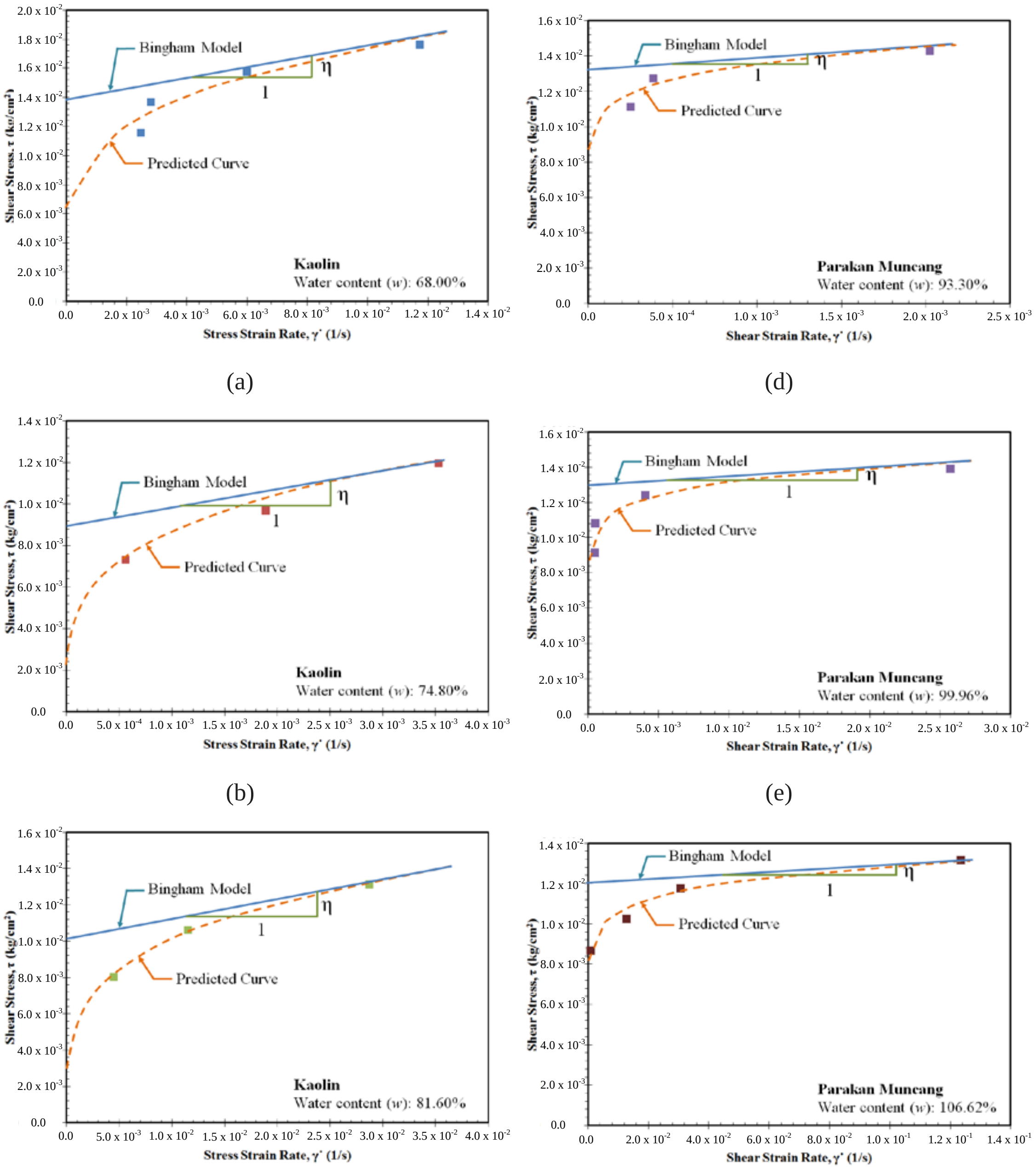
3. RESULTS AND DISCUSSION

The relationship between viscosity (η) and the liquidity index (*LI*) cannot be obtained directly. However, the Bingham model can be used to obtain η, as shown in Figure 5. Figure 6 shows the relationship between η and *LI*.

The η from the dashed line was obtained from Equation 2, that is, the shear stress and shear strain rate curve. This curve represents the real behavior of the soil. Then, the Bingham model was applied (represented by the solid line) to obtain the viscosity value from this model. The plotting method demonstrates the same tendency: that the gradient of the viscosity and liquidity index curves (dashed and solid curves) are similar (Figure 6). The viscosity value that is derived directly from the real behavior varies depending on the slope angle (the dashed line in Figure 6). In fact, the mud can have only a single value of viscosity at a certain value of water content. Therefore, the viscosity derivation from the Bingham model (the solid line in Figure 6) can be adopted for flowing material.

On the basis of the experiment results shown in Figure 6, and the condition that the mud can have only a single value of viscosity (η) at a certain value of water content (w) or liquidity index (*LI*), a single viscosity value can be obtained by plotting the shear stress–strain rate data, which was obtained in this study by varying the slope angle and then analyzing it by using the Bingham plastic material analysis (Figure 5). This demonstrates that Vallejo and Scovazzo's (2003) method cannot be used only on a single slope angle (β). Thus, the result of the Bingham plastic material analysis is the viscosity–liquidity index curve, as shown in Figures 6 and 7. Compared with Vallejo and Scovazzo's (2003) curve, the viscosity value of kaolin in this experiment has a smaller value for the same liquidity index. In comparison, Widjaja and Lee (2013) showed that the kaolin viscosity derived from the flow box test (FBT) is in the range of 238.48 Pa·s to 2.58 Pa·s for *LI* less than or equal to 1.0, and from 2.58 Pa·s to 0.28 Pa·s for *LI* from 1.0 to 2.25. In another study, Mahajan and Budhu (2008) showed that the η for kaolin soil derived from the fall cone penetration test is in the range of 515.92 Pa·s to 34.39 Pa·s for *LI* from 0.34 to 2.1. Compared with these previous studies (Widjaja& Lee, 2013; Mahajan & Budhu, 2008), the experiment results obtained using Vallejo and Scovazzo's (2003) method generate a relatively higher η.

Figure 7 shows that the viscosity–liquidity index curves of Parakan Muncang and kaolin soils exhibit the same gradients as the curves presented by Vallejo and Scovazzo (2003) and Mahajan and Budhu (2006), respectively. The η for the kaolin soil obtained in this experiment was in the range of 5.7×10^4 Pa·s to 1.2×10^4 Pa·s with *LI* ranging from 1.1 to 1.4. Having the same tendency as natural soil, the η for the ParakanMuncang soil was relatively higher than that for kaolin, which ranged from 6.4×10^4 Pa·s to 0.8×10^3 Pa·s for *LI* ranging from 1.7 to 2.0. The viscosity–liquidity index curves of Parakan Muncang and kaolin soils (Figures 6 and 7) also show that the sample with a higher percentage of clay-sized particles (Figure 3), which is the Parakan Muncang soil, has a higher viscosity than the other sample.



(a) (d)

(b) (e)

(c) (f)

Figure 5 Shear stress and strain rate curve analysis results of kaolin soil for water content: (a) 68.00%; (b) 74.80%;(c) 81.60%, and ParakanMuncang for water content: (d) 93.30%; (e) 99.96%; (f) 106.62%

On the basis of the definition and analysis of mudflow viscosity from the Bingham plastic material model (refer to Figure 4), the experiment results indicate that Vallejo and Scovazzo's (2003) method is a low shear strain rate test for obtaining viscosity that is representative of mudflow viscosity. The shear strain rate value for this method reaches as high as 0.35 and 0.12 s^{-1} for kaolin and Parakan Muncang, respectively. As such, Vallejo and Scovazzo's (2003) method is limited for low shear strain rate levels. This finding is close to the viscosity derived from the vane shear test, as shown by the circles numbered 13 and 14 in Figure 7 (Widjaja & Setiabudi, 2014), thereby implying that the vane shear test is also conducted for low shear strain levels as well. In comparison, according to Rajapakse (2008) and O'Brien (2003), the shear strain for mudflow could be as low as 5 s^{-1}, but this value can be obtained only by the Bingham model. The strain rate value depends on the recording of the instrument, particularly for wire/string displacement. The capability of the mud mass to move the string decreases along its downward movement because the mud mass at the source area has already been transported.

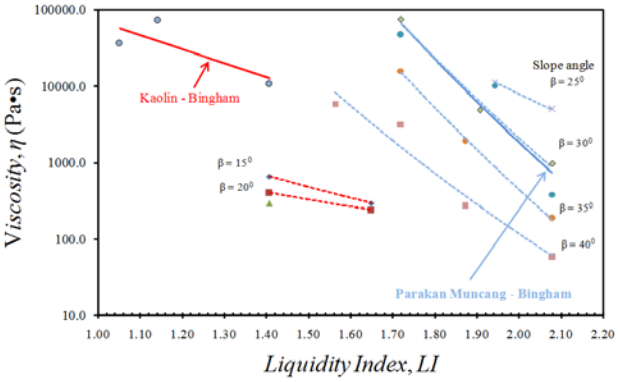


Figure 6 Viscosity–liquidity index curves of kaolin and Parakan Muncang soils

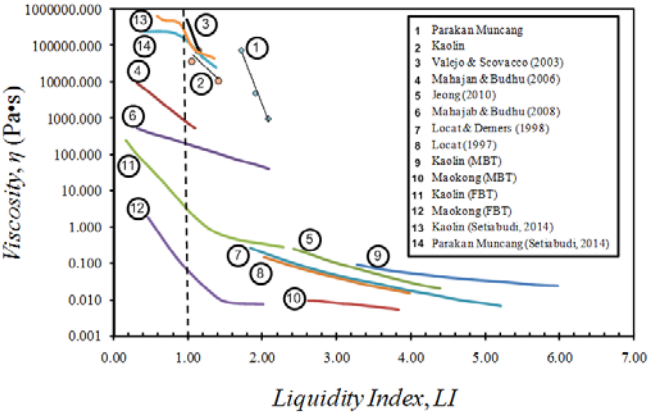


Figure 7 Comparison between the present study and previous research for kaolin and Parakan Muncang soils

Thereafter, Vallejo and Scovazzo’s (2003) formula in Equation 2 was used to address the variation of the slope angle. The equation also has a limitation: if the unit weight of the soil is smaller than the undrained shear strength at specific water contents, the change of the viscosity value will be inappropriate.

By adjusting the slope angle, the variation of the flow velocity and shear strain rate will be affected. From the statement that the change in velocity is a manifestation of the change in the stress level caused by the slope angle or the depth of mud, Equation 2 can be modified as follows:

$$V = \frac{\gamma_f h^2 \sin\beta - 2c_u h}{2\eta} \tag{3}$$

where η is viscosity (Pa·s), γ_f is the unit weight of mud (kN/m^3), h is the sample height (m), β is the slope of the sliding plane, c_u is the undrained shear strength of mud (kN/m^2), and V is the average velocity of the mud sample (m/s). Equation 3 is useful for determining the average velocity of mud when it moves at a certain unit weight, depth of mud, undrained shear strength, and viscosity of mud. However, this modification still faces the limitation of Equation 2. One advantage of this velocity equation is that it compares the velocity from the experiment with the real/numerical simulation from the mudflow event. Widjaja and Lee (2013) and Lee and Widjaja (2013) used numerical simulations to estimate the mudflow transportation time and velocity of mud.

4. CONCLUSION

The determination of viscosity value using Vallejo and Scovazzo's (2003) method is recommended for use at a low strain rate level while modifying the slope angle to vary the shear stress magnitude. Each shear stress magnitude obtains a certain value of shear strain rate data. Then, the shear stress–shear strain rate data are plotted into a shear stress (vertical axis) and strain rate (horizontal axis) curve, which is analyzed using a Bingham plastic material model to obtain the single value of the viscosity. However, Vallejo and Scovazzo's (2003) method requires a low strain rate level, which would produce a higher value of viscosity and may not represent real mudflow viscosity, unlike in previous studies. Moreover, Vallejo and Scovazzo's (2003) equation encounters a limitation in that, if the soil unit weight is smaller than the undrained shear strength for a specific water content, the viscosity value becomes unsuitable. By modifying Vallejo and Scovazzo's (2003) equation, the average velocity of the mudflow can be obtained if all of the input parameters (unit weight, mud depth, undrained shear strength, slope angle, and viscosity) are known. However, such a modification of the equation still cannot overcome the limitation of Vallejo and Scovazzo's (2003) equation itself. The contribution of this study is its evaluation of the accuracy of implementing the Bingham model in Vallejo and Scovazzo's method to determine the realistic viscosity for mudflow.

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