Scale effects on viscosity determination using flume channel based on Vallejo and Scovazzo Method

Budijanto Widjaja1, Ignatius Tommy Pratama1*, and Ian Hartono2

1Department of Civil Engineering, Universitas Katolik Parahyangan, Jl. Ciumbuleuit No. 94, Bandung, Indonesia
2Undergraduate Program in Department of Civil Engineering, Universitas Katolik Parahyangan, Jl. Ciumbuleuit No. 94, Bandung, Indonesia

Abstract. Mudflow is a type of ground movement that has a high speed and can occur suddenly. To learn more about mudflow movement, the need for analysis to obtain parameters of undrained shear strength and viscosity is important, especially viscosity, due to the limited available instruments. One approach to analysing mudflow is the rheological approach, which consists of two essential parameters: yield stress and viscosity. Research conducted by Vallejo and Scovazzo used a flume channel to determine the viscosity value of mudflow viscosity based on displacement and time of flow displacement. This study used the methods and formulas developed by Vallejo and Scovazzo with samples of kaolin and bentonite soils. The flume channels used are half-sized and quarter-sized from the original. The experimental results show that the viscosity value obtained from the Vallejo and Scovazzo Methods was relatively high because of the initial flow viscosity value. Further analysis using the Bingham plastic model shows that the viscosity obtained from the quarter-sized model was nearly 2 times smaller than the half-sized model. Meanwhile, the shear stress value of the half-sized model was about 2.3 times greater than the quarter-sized model.

1 Introduction

Indonesian Natural Disaster Management Agency (BNPB) categorizes landslides as one of the high-risk disaster threats. Based on data from the Indonesian National Disaster Management Agency (BNPB) from 2017 to 2021, landslides occupy the 3rd position in Indonesia's most frequent natural disasters [1]. According to Vallejo and Scovazzo [2], a classification system for landslides was made based on their soil and movement type. One of the classified landslides is mudflow. Mudflow is a type of ground movement with a high speed and can occur suddenly. Mudflow occurs when the water content value equals or exceeds its liquid limit. The boundary stability approach is a common method to analyse landslides’ stability, expressed in a safety factor. However, this method cannot explain the stress-strain rate relationship of mudflow material from the transportation to the deposition areas. One approach that can be taken to study mudflow movement behaviour is the rheological approach. It shows that the mudflow stress-strain rate relationship is affected by two parameters, namely yield stress (τy) and viscosity (η), as shown in Equation 1.

\[ \tau = c_u + \eta \frac{d\gamma}{dy} \]  

(1)

where \( c_u \) is the undrained shear strength and \( \frac{d\gamma}{dy} \) is the velocity gradient in the mudflow. Due to the limitations of conventional viscometers when measuring soil viscosity with water content (w) higher than their liquid limit (LL), Vallejo and Scovazzo [2] proposed a method to determine the soil η value using an 80 cm × 20 cm × 15 cm flume channel. Note that the study was limited to determining the η value of kaolin clay. Thus, this study adopted the methods and formulas developed to investigate the scale effects on the kaolin and bentonite soils η determination using a flume channel. This study used two (2) smaller flume channels with a scale of 0.5, denoted as a half-sized flume channel, and 0.25, represented as a quarter-sized flume channel, of the original flume size. The laboratory study was also conducted by varying the slope angles (β) and the w values of the kaolin and bentonite soil samples to obtain the η value at different applied shear stress and mud shear strength.

2 Literature study

2.1 Vallejo and Scovazzo viscosity in mudflow

In the study conducted by Vallejo and Scovazzo [2], a flume channel with a dimension of 80 cm × 20 cm × 15 cm was made from transparent plexiglass or acrylic. A partition or gate in the middle of the flume channel separated the source and mud transportation zones. Fig. 1 illustrates the flume channel used. Before placing the mud samples in the mud chamber or source zone (i.e., the right side of the flume channel in Fig. 1), strings were attached to the sides of the mud chamber to measure the displacement and velocity at different depths of mud samples. The strings were fixed to the bottom of the...
channel so that the velocity at the interface between the mud samples and the base of the flume channel was nil. Note that the side walls of the channel were also greased before the mud samples placement to avoid adhesion during the shearing phase. The flume channel was then placed on a tilting plane with a slope angle of 20° to 40°.

![Figure 1](image1.png)

**Fig. 1.** Dimension of flume channel used in [2].

The mudflow material shear stress-strain rate behavior was assumed to follow the Bingham plastic material behavior [3]. Thus, a relationship for estimating the \( \eta \) value of the mud moving down on an inclined plane can be established based on Equation 1, and it is presented by Vallejo and Scovazzo [2]. However, according to Widjaja and Pratama [4], some modifications to the \( \eta \) equation by Vallejo and Scovazzo [2] were required to satisfy the requirements of mathematical operation. Equation 2 shows the modified \( \eta \) equation.

\[
\eta = \frac{\gamma_f h^2 \sin \beta - 2 c_u h}{2(V_f - V_h)}
\]

where \( \eta \) is the viscosity of the mud (Pa·s), \( \gamma_f \) is the unit weight of the mud (N/m³), \( h \) is the depth of the mud sample (m), \( \beta \) is the slope of the test plane in degrees, \( c_u \) is the undrained shear strength of the mud (N/m²), \( V_f \) is the velocity at the surface of mudflow (m/s), and \( V_h \) is the velocity at the interface between the mud samples and the sliding plane (m/s).

### 2.2 Bingham plastic model

The Bingham plastic model is a material model that belongs to the Non-Newtonian Fluids. The material in the Bingham plastic model behaves like a solid object. Still, its behavior changes to a viscous liquid when given a stress exceeding its limit (yield stress). One example of an object included in the Bingham plastic model is the yield stress value for both soil samples was assumed to be the same as the undrained shear strength \( (c_u) \). In this study, the \( c_u \) values were obtained using the cylinder-strength meter test presented by Vallejo and Scovazzo [2] due to the limitation of the conventional laboratory strength test methods (e.g., triaxial, direct shear, and unconfined compression tests) in determining the \( c_u \) of mud. The cylinder-strength meter test concisely measured the \( c_u \) of the mud samples based on the penetration of a smooth cylinder with a particular dimension and weight. Fig. 6 displays the measured \( c_u \) for various liquidity indexes (LI).

Two flume channels were used in this study, a half-sized flume channel with a respective size of 40 cm × 10 cm × 7.5 cm and a quarter-sized flume channel with a respective size of 20 cm × 5 cm × 3.25 cm. Note that the 7.5 cm and 3.25 cm were the height of the mud samples in the half-sized and quarter-sized flume channels. Strings were attached to the bottom of the flume channel on each side of the flume channels. This allowed no strings

![Figure 2](image2.png)

**Fig. 2.** Bingham Plastic Model and real materials [5].

### 3 Experimental methods

Fig. 3 exhibits the experimental flowchart used in this study. As shown in Fig. 3, this study was initiated with a literature study followed by the flume channels and the soil samples preparation. The tests used two soil samples, namely kaolin and bentonite soils. Both soil samples were obtained in powder form from a local store in West Java. Several initial laboratory tests (i.e., index properties tests, grain size analysis, hydrometer tests, and fall cone penetrometer tests) were then carried out to identify the physical properties of the kaolin and bentonite soils. Fig. 4 shows the kaolin and bentonite soil samples and the initial laboratory tests.

Table 1 lists both kaolin and bentonite soils’ parameters. Then, Fig. 5 shows the kaolin and bentonite grain size distributions. According to the grain size distributions in Fig. 5, more than 50% of the kaolin and bentonite soil particles passed the No. 200 sieve, which was 99.9% for the kaolin soil samples and 89.8% for the bentonite soil samples. Thus, both kaolin and bentonite soils used in this study were classified as silt with high plasticity (MH) according to the Unified Soil Classification System (USCS) [6].

The yield stress value for both soil samples was assumed to be the same as the undrained shear strength \( (c_u) \). In this study, the \( c_u \) values were obtained using the cylinder-strength meter test presented by Vallejo and Scovazzo [2] due to the limitation of the conventional laboratory strength test methods (e.g., triaxial, direct shear, and unconfined compression tests) in determining the \( c_u \) of mud. The cylinder-strength meter test concisely measured the \( c_u \) of the mud samples based on the penetration of a smooth cylinder with a particular dimension and weight. Fig. 6 displays the measured \( c_u \) for various liquidity indexes (LI).

![Figure 3](image3.png)

**Fig. 3.** Experimental flowchart used in this study.
displacement reading at the bottom of the flume channels. The strings were placed with 5 cm spacing for the half-sized flume channel to obtain a more precise displacement reading. Meanwhile, for the quarter-sized flume channel, the first strings were situated 3 cm away from the ends of the flume channel. Then, the second strings were 2 cm away from the first or 5 cm from the gate. Note that, in this study, the strings were attached to walls in the source zone and in the transportation zone to measure the average mud flow velocity. Fig. 7-8 illustrate this study's flume channels and strings configuration.

![Flow Chart](image)

**Fig. 3.** Experimental flowchart.

**Fig. 4,** (a) sample preparation, (b) fall cone penetrometer test, (c) specific gravity test, and (d) sieve analysis.

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Symbol</th>
<th>Soil Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Kaolin</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>PL</td>
<td>49.62</td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>LL</td>
<td>73.10</td>
</tr>
<tr>
<td>Plastic Index</td>
<td>PI</td>
<td>23.48</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>$G_s$</td>
<td>2.64</td>
</tr>
</tbody>
</table>

The experiment began by finding the $w$ and $\beta$ values where the mud started to flow. The initial water content was determined by making the water content close to the LL of the soil samples. The water and soil samples should be mixed thoroughly to turn the mixture into homogeneous mud. Next, the mud water content was tested to verify that the actual water content ($w_{\text{act}}$) was close to the theoretical estimated water content ($w_{\text{est}}$). Then, the rest of the soil sample was placed in an air-tight container for about 24 hours to avoid changes in the sample water content and to let the water seep into the soil pores.

The samples (kaolin and bentonite) were placed in the flume channel and then tested for the slope of the first observed flow. The tested slope angle started from $20^\circ$ to $40^\circ$ at maximum. If the $40^\circ$ slope angle had not been reached, the trial mudflow test was continued for the same mud water content by increasing the slope angle by $5^\circ$. However, suppose the mud sample with the designated water content still did not flow at the maximum slope angle (i.e., $40^\circ$). In that case, the water content of the mud should be increased, and the trial test should be started from the smallest slope angle (i.e., $20^\circ$).
Fig. 5. Grain size distribution of the kaolin and bentonite soil samples.

Fig. 6. Trends of $c_v$ with LI for kaolin and bentonite soil samples.

Fig. 7. Half-sized flume channel.

Based on the trial test results, the required water content for the kaolin sample to first flow was 1.5LL at a 40° slope angle, whereas, for the bentonite sample, the required water content and slope angle to first flow were LL and 20°, respectively. Later, the variations of the water content and the slope angles for the kaolin and bentonite soil samples are listed in Table 2.

In the testing phase, after the samples were ready, the strings were attached to the inner wall of the flume channel. Two cameras were situated in front of and beside the flume channel to capture the displacement of the mud samples and the strings. The soil mixture was then placed in the flume channel, followed by tilting the flume channel. The flume channel gate was then opened to let the mud sample flow down on the inclined plane gravitationally, and at this condition, the mud flow time started counting. The flow time was recorded until no mud movement was observed. Fig. 9-10 show the flume channel test setup and the typical flow test results on kaolin and bentonite soil samples, respectively. The recorded displacement and mud travel time were eventually used to compute the $\eta$ values using Equation 2.

Fig. 8. Quarter-sized flume channel.

Fig. 9. Flume channel test setup.
Vallejo and Scovazzo [2] expressed a mathematical model based on the forces acting on the moving mud sample on the inclined slope. It was assumed that the frictional forces between both sides of the flume channel and the adhesion force were ignored, and only the friction between mud samples and the bottom of the flume channel were calculated. As a result, Equation 4 could be used to express the $\tau$ equation for estimating the shear stress value. The shear stress and strain rate values of a mudflow were also estimated from this experiment.

$$\tau = \gamma_f h \sin \beta \quad (4)$$

Meanwhile, the $\gamma$ value was obtained based on Equation 5.

$$\gamma = \frac{dv}{dy} = \frac{(V_t - V_b)}{h} \quad (5)$$

Substituting Equations 4-5 to Equation 3 and assuming that $\tau_y$ was equal to $c_u$, Equation 2 was obtained.

### 4 Results and discussion

Fig. 11 compares the samples' actual water content ($w_{act}$) and estimated water content ($w_{est}$). The $w_{act}$ in Fig. 11 defines the water content of the kaolin or bentonite soil samples used during the laboratory test. Meanwhile, $w_{est}$ was the targeted water content which was computed based on the LL value of the kaolin or bentonite soil samples. Fig. 11 shows that the differences between the $w_{act}$ and $w_{est}$ were negligible (i.e., below 5%), indicating that the magnitude of the water content in the tests was close to the targeted water content.

![Fig. 11](image)

**Fig. 11.** Comparison of actual water content ($w_{act}$) and estimated water content ($w_{est}$).

Analysis of the shear stress-strain rate of the mud samples to determine the $\eta$ values was then performed by assuming that the shear stress-strain rate of the mud followed the Bingham plastic model. This analysis was later denoted as the Bingham plastic model analysis. Fig. 12-15 show the Bingham plastic model analysis results for the tests using the half-sized and quarter-sized flume channels for the kaolin and bentonite soil samples.

![Fig. 12](image)

**Fig. 12.** Bingham plastic model analysis of kaolin sample on the half-sized flume channel.

### Table 2. Parameters of kaolin and bentonite soil samples.

<table>
<thead>
<tr>
<th>Soil Samples</th>
<th>Water Content (w)</th>
<th>Slope Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolin</td>
<td>1.5LL</td>
<td>40°</td>
</tr>
<tr>
<td></td>
<td>1.6LL</td>
<td>40°</td>
</tr>
<tr>
<td></td>
<td>1.7LL</td>
<td>20°, 30°, 40°</td>
</tr>
<tr>
<td></td>
<td>1.8LL</td>
<td>20°, 30°, 40°</td>
</tr>
<tr>
<td></td>
<td>1.9LL</td>
<td>20°, 25°, 30°, 35°, 40°</td>
</tr>
<tr>
<td></td>
<td>2.0LL</td>
<td>20°, 25°, 30°, 35°, 40°</td>
</tr>
<tr>
<td>Bentonite</td>
<td>LL</td>
<td>20°, 25°, 30°, 35°, 40°</td>
</tr>
<tr>
<td></td>
<td>1.1LL</td>
<td>20°, 25°, 30°, 35°, 40°</td>
</tr>
<tr>
<td></td>
<td>1.2LL</td>
<td>20°, 25°, 30°, 35°, 40°</td>
</tr>
</tbody>
</table>
Table 3 lists the \( \eta \) values of the kaolin and bentonite soil samples for different water content on quarter-sized and half-sized flume channels obtained from the Bingham plastic model analysis in Fig. 12-15. The results in Table 3 show that higher LI values produced lower \( \eta \) values for kaolin and bentonite muds (i.e., the mud became more liquid). Furthermore, the \( \eta \) values on the half-sized flume channel were about two times higher than the \( \eta \) values on the quarter-sized flume channel. It is also apparent in Fig. 12-15 that the \( \tau_y \) values for the same material and water content differed from the one measured for the quarter-sized flume channel to the one measured for the half-sized flume channel. It was then argued that the mud samples in the half-sized flume channel behaved as a stiffer material than in the quarter-sized flume channel. However, this statement could not be accurate. Suppose the \( \eta \) value is unique to a material with a particular water content. Still, the results signified that the size of the flume channel affected the \( \eta \) measurement.

<table>
<thead>
<tr>
<th>Soil Samples</th>
<th>Quarter-Sized Flume Channel</th>
<th>Half-Sized Flume Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>LI (LI)</td>
<td>( \eta ) (Pa( \cdot )s)</td>
<td>LI (LI) ( \eta ) (Pa( \cdot )s)</td>
</tr>
<tr>
<td>Kaolin</td>
<td>2.99</td>
<td>14,530.3</td>
</tr>
<tr>
<td></td>
<td>3.13</td>
<td>7,877.8</td>
</tr>
<tr>
<td></td>
<td>3.65</td>
<td>5,939.6</td>
</tr>
<tr>
<td></td>
<td>3.73</td>
<td>5,329.5</td>
</tr>
<tr>
<td></td>
<td>4.19</td>
<td>3,867.8</td>
</tr>
<tr>
<td></td>
<td>0.99</td>
<td>2,104.5</td>
</tr>
<tr>
<td></td>
<td>1.40</td>
<td>2,075.2</td>
</tr>
<tr>
<td></td>
<td>1.64</td>
<td>1,966.4</td>
</tr>
</tbody>
</table>

Fig. 16 compares the \( \eta \) values of the kaolin and bentonite mud based on the Bingham plastic model analysis to the \( \eta \) values by Vallejo and Scovazzo [2] and Widjaja and Pratama [4]. Fig. 16 clearly shows that the obtained \( \eta \) values for the kaolin soil samples in this study were smaller than those obtained by Vallejo and Scovazzo [2]. This was because the \( \eta \) measurement using the method presented by Vallejo and Scovazzo [2] was derived from the shear stress and strain rate values at the onset of flow or the immediate elastic response [4]. Meanwhile, the Bingham plastic model analysis uses shear stress and strain rate values at the steady viscous response point. Therefore, the \( \eta \) values by Vallejo and Scovazzo [2] were larger than the \( \eta \) values in this study.

Then, the \( \eta \) values in this study were higher than the results obtained for kaolin soil by Widjaja and Pratama [4] for LI > 1.5, where the researchers by Widjaja and
Pratama [4] used the same flume dimension as used by Vallejo and Scovazzo [2] to determine the \( \eta \) values of kaolin mud. However, it was worth noting that the gradient of the changes of the \( \eta \) value to the LI of the kaolin mud in this study was relatively similar to those obtained by Widjaja and Pratama [4]. It implies that the size of the flume channel influenced the magnitude of \( \eta \), but not the trend of \( \eta \) vs. LI.

In addition, the change of the \( \eta \) values with LI of the bentonite mud for both the quarter-sized and half-sized flume channels in Fig. 16 was relatively negligible compared to the trend for the kaolin mud. Further verification, for instance, using the 1:1 or larger flume channel model, was still required to verify the findings.

Fig. 17-18 display the average shear stress (\( \tau_{av} \))-strain rate (\( \dot{\gamma}_{av} \)) relationship of the kaolin and bentonite soil samples, respectively. Fig. 17-18 verified that increasing the size of the flume channel increased \( \tau \) and \( \dot{\gamma}_{av} \) values logarithmically. It could be related to the friction between mud samples and the sides of the flume channel. The method by Vallejo and Scovazzo [2] assumed that friction only occurred between the sample and the bottom of the flume channel. It was worth noting that the contact surface area of the half-sized flume channel was larger than the quarter-sized flume channel. This condition resulted in the shear stress values on the half-sized flume channel being about 2.3 times larger than those on the quarter-sized flume channel. Then, the length of the quarter-sized flume channel and the sample height in the quarter-sized flume channel were shorter than the half-sized model. It implies that the strain rate of the quarter-sized model was at the initial flow conditions and had not yet reached stable and true flow conditions. Meanwhile, the strain rate obtained in the half-sized flume channel was closer to the steady viscous state condition. Thus, using a larger flume channel to measure the \( \eta \) value of a mud sample was recommended for a different rheological approach to study mudflow behavior in the field.

Furthermore, the larger the flume channel model used in the test, the greater the shear stress and strain rate values obtained and vice versa. The larger the contact surface area of the model produced, the greater the friction between the test sample and the flume channel wall. Larger the model also had a longer mud travel distance causing the strain rate to become closer to the steady viscous state condition. Eventually, the results of this study were valid for homogeneous mud with properties comparable to kaolin or bentonite soils. The findings of this research could advance the understanding of mudflow behavior and factors affecting the measurement of mud parameters, especially mud viscosity. This research could also be used as a reference in future studies, especially those related to developing mud viscosity measurement correction factors.

### 5 Conclusion

This paper studied the scale effects on the kaolin and bentonite mud viscosity measurement using Vallejo and Scovazzo’s Method. The flume used in this study was 2 and 4 times smaller than the flume channel used in the previous study. The results indicated that the viscosity value obtained in the previous study was at the initial flow condition resulting in a higher viscosity. The viscosity value should be determined at a steady viscous state or when the flow stabilizes and moves freely. The limitations of the flume channel test could be overcome by using the Bingham plastic model analysis to obtain the viscosity value of the test sample at a steady viscous state. Then, decreasing the scale of the flume channel model affected the mud viscosity, shear stress, and strain rate values. The mud viscosity values measured using the half-sized flume channel were about two times larger than those obtained from the quarter-sized flume channel measurements. However, larger water content produced a smaller viscosity value for both kaolin and bentonite mud samples. Then, according to the relationship between the viscosity of the mud and the liquidity index, it was found that the size of the flume channel only affected the magnitude of the mud viscosity but not the trend changes of the mud viscosity with the liquidity index.

Fig. 18. Average shear stress and strain rate comparison on bentonite soil samples.


References

3. A.M. Johnson, Physical Processes in Geology (Freeman, Cooper, 1970)