

Landslide and Mudflow Behavior Case Study in Indonesia: Rheology Approach

Budijanto Widjaja

Abstract—Landslides and mudflows, both of which are triggered by rainwater and earthquakes, frequently occur in Indonesia. However, a conceptual and analytical understanding of these phenomena has yet to be achieved. The conventional calculation method (i.e., the limit equilibrium method) has not been able to predict the affected area after a landslide. Therefore, a rheological approach, the Bingham model (yield stress and viscosity), was applied in this research. Twelve cases of soil movement were assessed. High-plasticity silt is a type of fine soil with the potential to cause landslides and mudflows. This study comprises field data collection, soil sampling, laboratory testing, numerical modeling with a specific software, and result analyses. This study contributes explanation for the movement mechanism based on soil type, source area position to deposition area. New test laboratory innovation (flow box test) was introduced, and landslide and mudflow classification based on rheology approach were proposed. Examples of soil movement mitigation strategies are also presented to provide an overview of protective efforts against landslides and mudflows.

Keywords—silt, landslide, mudflows, rheology.

I. INTRODUCTION

Soil movements, such as landslides and mudflows, occur frequently around the world, especially in Indonesia. However, current concepts and analytical studies are still unable to explain these phenomena. For example, in the limit equilibrium method, landslide calculations are limited only to the ratio between shear strength and shear stress, which is commonly referred to as the safety factor (SF). However, this method only provides critical slip surface and safety information against the landslide; the condition after soil movement is not explored. Then, further research is needed to elucidate the behavior of soil movement by using another approach (i.e., rheology). The rheological approach shows good model to describe the current conditions of transport and deposition after a landslide occurs. In this paper, soil movement is divided into three section: source, transportation, and deposition/accumulation area, as shown in Fig. 1.

II. SOIL MOVEMENT DEFINITION

The morphological form of the earth's surface is produced by nature and human intervention. Moreover, soil conditions, such as variations in water content due to weather changes (e.g., rainfall infiltration), markedly influence the soil profile.

Soil movement can be defined as the process occurring on the earth's surface to achieve a new equilibrium. This process involves soil and rock landslides, including mudflow. Fig. 2 shows a geological view of typical soil movements based on water content and transportation velocity.

A. Safety Factor: The Ratio of Slope Safety Determination

Calculations of landslides in the geotechnical literature generally use the limit equilibrium method and phi-c reduction method. Both methods use shear strength parameters (e.g., cohesion and angle of internal friction) as a basis for analysis. The result obtained is the ratio of shear strength to working shear force and called SF, as shown in Fig. 3. The acceptance criterion in the design is an SF greater than the minimum required SF (for example, minimum SF is 1.5).



Figure 1. Parts of soil movement [1].

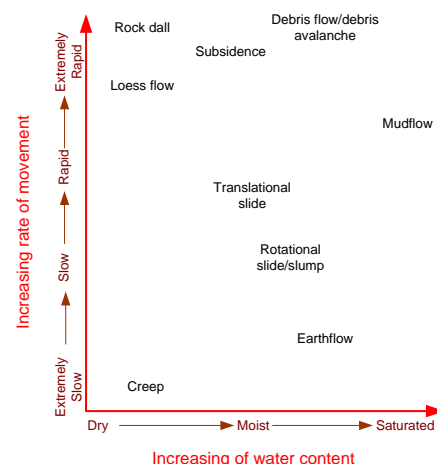


Figure 2. Soil movement as function of water content and speed of movement [2].

Budijanto Widjaja is with Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung, Indonesia. E-mail: widjaja@unpar.ac.id.

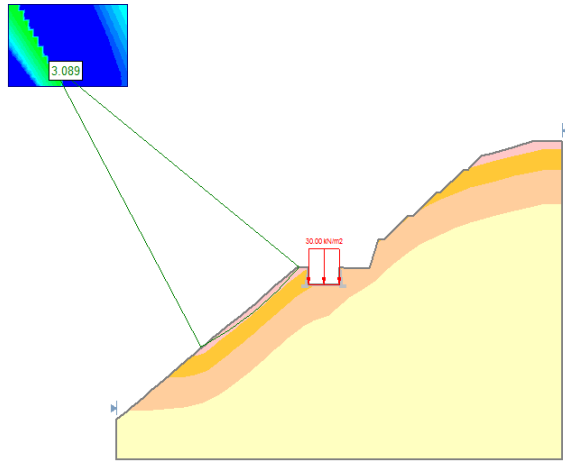


Figure 3. Typical analysis results for determining slope safety factor.

As the advantage, this method only uses a simple cross section in plane strain conditions and simple calculations to determine value of safety factor (SF). However, the disadvantages are as follows:

1. Soil parts that experience landslides are considered as rigid materials, and the slip surface can take on the form of translations, rotations, or blocks. This consideration contrasts with the fact that the soil material is compressible. Specifically, for limit equilibrium analysis, e.g. Fellenius and Bishop methods, analyses are performed using the concept of static equilibrium (and/or pseudostatic analysis for dynamic analysis) between wedges. A common constitutive model is the Mohr-Coulomb model.

2. The analysis results generally give the smallest SF information for the wedges analyzed. However, the affected area is not known due to the triggered landslide. The study area is limited at the source area part. Moreover, the locations of the transportation and sedimentation areas are still unknown.

Some questions that may arise after a landslide are as follows: Where will the soil mass routed to? How does the soil flow route trigger? How big is the area affected? These questions, however, have not been answered using the SF approach.

B. Research Method: Rheology Approach

To address the questions above, rheology, which studies how a flow occurs and moves, can be employed. Two important parameters in this model are yield stress (τ_y) and viscosity (η). A new flow occurs if the shear stress (τ) is greater than τ_y . Afterward, the flow velocity is determined by η . A material which has no yield stress (e.g., water), is called a Newtonian material. A material that possesses both parameters is known as a non-Newtonian material. Thus, soil material can be categorized as non-Newtonian material.

An example of the application of the rheology model in geotechnics is the explanation of consolidation, in which the soil is modeled as a retained spring in a container, where water can dissipate via certain holes in the upper part of the container. Dynamic formula from Newton also uses a

combination of spring, dashpot, and mass. As such, rheology is similar to the use of spring, dashpot, or other types, such as slider friction.

One of the simplest rheological models that can be used for non-Newtonian materials is the Bingham model, which uses combination among spring, friction block, and dashpot, to explain the movement behavior of a material, as shown in Fig. 4.

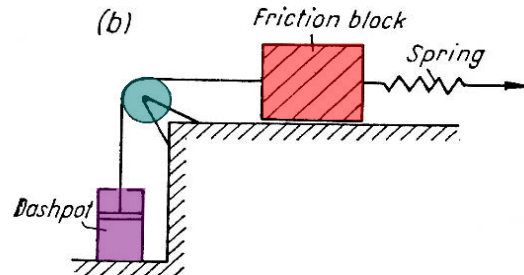


Figure 4. Bingham model [3].

Similar to soil constitutive models (e.g., the Mohr Coulomb model) which expresses the stress-strain relationship, rheological model uses the relationship between shear stress and shear strain rate. The shear strain rate is the first derivative of shear strain, which commonly used in constitutive relationships for dynamic problems (e.g., shear modulus). As shown in Fig. 5, real materials in the field, especially soil, follow a curve pattern similar to the case of strain hardening soil. The gradient at any point in the curve is a representation of the viscosity (η). As such, η varies due to the soil movement that occurs after the τ passes τ_y .

The Bingham model is a simple model and η is considered constant during movement (Fig. 5). During transportation, the slip surface is affected by two values, i.e. surface roughness and viscosity. Parametric test results reveal that the average viscosity can be represented by a constant viscosity without a remarkable change in predicted deposition results (or soil mass movement under a high shear strain rate). If the soil surface is excessively rough then the soil flow is controlled by a lower parameter i.e., η . Generally, after soil deposition, the controlled parameters are the shear stress (τ) and surface roughness. Hence, the Bingham model can be used to predict landslide and mudflow behavior, especially in transport and deposition area simulations.

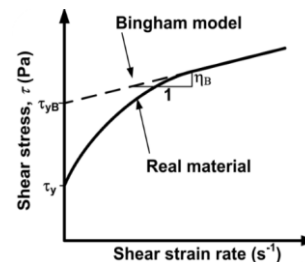


Figure 5. Real material behavior and Bingham model.

In this research, the soils are mostly in the form of fine grains. Therefore, τ_y can be represented by the cohesion (c_u). When determining c_u , due to the range of soil conditions

TABLE 1.
SOIL TYPES IN LANDSLIDE AND MUDFLOW RESEARCH

No.	Sample	LL	PL	G _s	Soil type	Soil Movement Types
1	Kaolin*	68	38	2.61	MH	Laboratory test (flume channel)
2	Bentonite*	208	115	2.67	CH	Laboratory test (flume channel)
3	Karanganyar (2007)	53	34	2.71	MH	Mudflow
4	Maokong (2008)	33	26	2.66	ML	Mudflow
5	Ciwidey (2010)	45	32	2.63	ML	Mudflow
6	Sukaresmi, Cianjur (2013)	66	48	2.55	MH	Mudflow
7	Cililin (2013)	58	30	2.74	MH	Mudflow
8	Parakan Muncang (2014)	67	29	2.60	CH	Landslide
9	Karang Mukti (2014)	88	29	2.67	CH	Landslide
10	Banjarnegara (2014)	65	40	2.73	MH	Mudflow and landslide
11	Parung Ponteng (2014)	63	51	2.64	MH	Mudflow
12	Pangalengan (2015)	95	68	2.76	MH	Mudflow
13	Purworejo (2016)	74	38	2.56	MH	Mudflow
14	Ponorogo (2017)	60	45	2.74	MH	Mudflow

from the plastic state to the viscous liquid state, a combination of the unconfined compression test (if applicable), vane shear test and fall cone penetrometer test was used in the early stages of this research. Especially for the fall cone penetrometer test, empirical formulas are used to determine τ_y . Results show that the range of c_u can be represented by the results of the fall cone penetrometer test after being compared with those of the two other test types [4][5], and [6].

The soil samples obtained in this research were, on average, between the source and deposition areas. This sample is generally a disturbed/remolded sample. Physical parameters (water content, density, sieve analysis and hydrometer, Atterberg limits) are derived from that type of sample.

By applying a rheological approach to landslide analysis, transport and deposition zones can be identified. Therefore, the topography map of the site under review, soil rheology parameters, soil surface conditions (e.g., with dense vegetation), and landslide volumes are included as inputs.

C. New Innovation for Rheological Parameter Determination

To determine rheological parameters, i.e., τ_y and η , conventional viscometer test can be used in the laboratory. The basic principle of this test varies, for example a rotary system type. However, it is generally only applicable for soil conditions with liquidity index (LI) higher than 2. The thickness of soil cannot represent actual soil conditions due to a preparation of thin sample in laboratory. In practice, when coarse grains are available in the sample, this test may not be applicable.

The first pilot project involved the development of a laboratory test is known as the moving ball test (Fig. 6 (left)). This test used the equilibrium principle when the velocity of the sphere embedded in the sample reaches the terminal velocity. Using Navier–Stokes equation, one can get soil rheological parameters. However, this test was not very effective, because it requires large quantities of soil and is specifically used for soils with LI higher than 2 [7].

To overcome the weaknesses of these test, a second laboratory test, called the flow box test (FBT), was developed, as shown in Fig. 6 (right). The governing equations used as a combination of both Terzaghi trap door

theory and the Bingham model. Using this test, the viscosity of a flow can be determined if the yield stress is known. A detailed explanation of this test is provided in [8] and [9].

Typical FBT test results are shown in Fig. 7. Using this test, landslide and mudflow characteristics were determined due to water content change.

D. Landslide and Mudflow Research in Indonesia

1) Triggers: Rainfall and Earthquake

The occurrence of landslides and mudflows is generally triggered by high amounts of rainfall and/or earthquakes. The soil movement may occur when the cumulative rainfall reaches more than 200 mm. An earthquake can trigger soil movement because it releases energy, which may cause cracks in the source area. These cracks later become a path for water infiltration and flow, then it will weaken the soil shear strength.

2) Typical Soil Types for Landslide and Mudflow

Eleven locations of soil movement are investigated in Indonesia (Table 1). The soil type at the source and deposition area sites is mostly silt with high plasticity (MH). Compared to clay type, the collapse pattern of silt occurs in the form of flow under a change in water content [10]. By contrast, the collapse pattern of clay (CH) is due to high soil sticky; the collapse pattern is similar to a landslide pattern, in which some parts experience bulging. These concepts were proven by using flume channels in the laboratory [11][12]. Hence, temporary conclusions indicate that silt in the source area tends to behave as a mudflow; by contrast, clay tends to behave as a landslide.



Figure 6. Moving ball test equipment (left) and flow box test (right) [9].

3) Similarity of Soil Types among the Source, Transportation, and Deposition Areas

Soil samples were obtained from the source, transportation, and deposition areas. As some of the soil in the source area eventually reaches the deposition area, the soil type between the two areas is relatively similar. The location of soil movement in Pengalengan shows this behavior [1].

4) Mechanism of Landslide and Mudflow Movement

As the soil moves and/or flows against the barrier in front of it, it tends to carry other larger materials, such as rocks and trees. Some research indicates that, at the time soil mass moves, the pattern of size distribution is reversed. Larger gradations move toward the flow surface, while smoother ones move toward the bottom. This phenomenon is caused by the buoyancy effect when flow occurs. Thus, although landslides and mudflows carry larger rock sizes, the mass weight is held by finer materials, such as clay or silt. Therefore, yield stress and viscosity determine behavior of mass movement at the border between the mudflow/landslide slip boundary and soil surface [13].

Soil in the source area has a certain water content and this result is based on the concept for single value of η . However, in the event of movement, the source area tends to be controlled by certain LI . When mass movement occurs, slip surface will tend to find a slip surface with the lowest shear strength. This shear strength is represented by rheological parameters, i.e. τ_y and η .

The landslide and mudflow cases analyzed in this research primarily use the Bingham model. However, the present research also compares the Bingham model with the Herschel-Bulkley model. Both models result in a decreased viscosity and a similar range of certain shear strain rates [14].

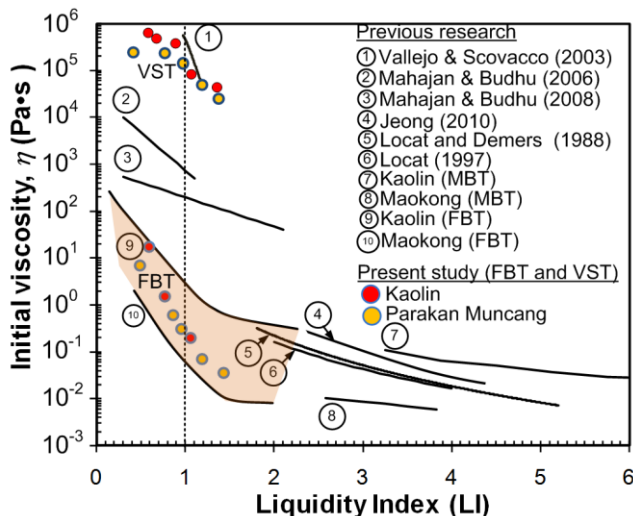


Figure 7. Real material behavior and the Bingham model [9].

5) Proposed Classification of Soil Movement

Based on the research results of landslides and mudflows in Indonesia, a classification of soil movement can be proposed. For locations in Indonesia, as proposed by [15] and modified by [9] and [12] under saturated water conditions, a concentration by volume (C_v) value within the

range of 0.35–0.55 can indicate a mudflow and a C_v value above 0.55 can indicate a landslide.

$$C_v = \frac{1}{1 + G_s w} \quad (1)$$

Based on the yield stress and viscosity determined, as well as FBT results, soil movement is classified as a landslide if LI is lower than 1; and for mudflow LI is higher than 1.

For mudflows, the ratio of average width of mudflow/landslide to length from source to deposition area is between 0.05–0.30; for landslides, this ratio is above 0.30. These findings imply that the mudflow transport distance is longer than the landslide transport distance and could reach 2–20 times the average flow width of the latter.

6) Landslide and Mudflow Mitigation

Countermeasures for landslide and mudflow events are practically identical to those for handling or maintaining landslide instability. Buildings or dams used to hold lahar (i.e., Sabo dams) must be prepared when a threat of mudflow arises. Further studies are needed to examine the magnitude of the impact force when mudflow hits a barrier building. The retaining buildings may be constructed in location which is vulnerable to mudflow events.



Figure 8. Layout installation of retaining buildings [16].

7) Advanced Research

Advanced research includes the formation of new volcanoes (mud volcano) [17][18], pile erection, modeling using the rheological approach [13], proposed classification soil for liquefaction using the rheological approach [19], and dam break analysis, such as the Sidoarjo mud embankment [20]. Moreover, rheological models other than the Bingham model are continuously being developed. The microbehavior of fine grains, such as silt and clay, in specific surface areas is also an interesting research topic [21].

III. CONCLUSIONS

Landslide and mudflow research in Indonesia provides a preliminary understanding of these phenomena. Soil types, soil movement mechanisms, and new soil classification recommendation present a comprehensive overview of landslide and mudflow behaviors based on specific cases of soil movement in Indonesia. Some examples of soil movement mitigation strategies are presented to provide an overview of protective efforts against landslides and mudflows. Based on 11 case studies, silty soils are prone to be mudflows rather than landslides. Mudflow may transport

materials to areas about 2–20 times larger than the average flow width of landslides.

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