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Correlations between rheological parameters and L-Box test parameters of woody-debris suspensions

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Abstract. Debris flows mobilize large volumes of water, sediment, and woody debris, posing significant hazards to human communities and infrastructure. In forested areas impacted by wildfires, the recruitment of woody debris into drainage channels is accelerated, increasing the potential for more hazardous debris flows. Rheological characteristics play a crucial role in understanding and simulating debris flow behavior. Debris flows consist of complex and heterogeneous materials with particle sizes ranging from clay to boulders. However, conventional rheometers are typically limited to measuring the rheological parameters of debris flows containing only fine particles. The L-box tests have been utilized to assess the flow behavior of woody-debris suspensions, accommodating sediments with larger particles. This study investigates the relationship between rheometer measurements and L-box test parameters for debris flows containing woody debris. The tests were conducted using woody-debris suspensions, which are mixtures of woody debris, clay, silt, and water. The rheological parameters of woody-debris suspensions were measured using the "Brookfield DV-III rheometer". The rheological behavior of the sediment suspensions in this study follows the Bingham fluid model. The rheological parameters, such as yield stress (τ_B) and viscosity (μ_B), are affected by the woody debris size (S_w) and woody debris proportion (C_{vg}), with larger S_w and lower C_{vg} leading to decreased rheological parameters. The L-box test was performed using the same woody-debris suspensions prepared for rheometer measurements, with flow height (H_f) and flow distance (L_f) recorded. The results indicate that as woody debris size increases and its proportion decreases, the flow height ratio (H_r) decreases, while the spread ratio (L_r) increases. Furthermore, the results demonstrate a strong correlation between the parameters obtained from rheometer measurements and those from L-box tests for the woody-debris suspensions in this study. This suggests that the L-box test as a practical alternative for estimating the rheological parameters of debris flows containing larger woody debris.

Key words: *rheological parameters, woody-debris suspensions, Bingham model, L-box test*

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Корреляции между реологическими параметрами и параметрами теста L-Box для суспензий с обломками деревьев

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Аннотация. Селевые потоки мобилизуют большие объемы воды, осадков и древесного мусора, представляя значительную опасность для человеческих сообществ и инфраструктуры. В лесных районах, затронутых лесными пожарами, поступление древесного мусора в дренажные каналы ускоряется, что увеличивает потенциал для более опасных селевых потоков. Реологические характеристики играют решающую роль в понимании и моделировании поведения селевых потоков. Селевые потоки состоят из сложных и неоднородных материалов с размерами частиц от глины до валунов. Однако обычные реометры, как правило, ограничиваются измерением реологических параметров селевых потоков, содержащих только мелкие частицы. Тесты L-box использовались для оценки поведения потока суспензий древесного мусора, вмещающих отложения с более крупными частицами. В этом исследовании изучается связь между измерениями реометра и параметрами теста L-box для селевых потоков, содержащих древесный мусор. Тесты проводились с использованием суспензий древесного мусора, которые представляют собой смеси древесного мусора, глины, ила и воды. Реологические параметры суспензий древесного мусора измерялись с помощью реометра «Brookfield DV-III». Реологическое поведение суспензий осадков в этом исследовании следует модели жидкости Бингама. Реологические параметры, такие как предел текучести (τ_B) и вязкость (μ_B), зависят от размера древесного мусора (S_w) и доли древесного мусора (C_{vg}), при этом больший S_w и меньший C_{vg} приводят к снижению реологических параметров. Тест L-box проводился с использованием тех же суспензий древесного мусора, подготовленных для измерений реометром, с регистрацией высоты потока (H_f) и расстояния потока (L_f). Результаты показывают, что по мере увеличения размера древесных остатков и уменьшения их доли отношение высоты потока (H_r) уменьшается, в то время как отношение распространения (L_r) увеличивается. Кроме того, результаты демонстрируют сильную корреляцию между параметрами, полученными из измерений реометра, и параметрами, полученными из тестов L-box для суспензий древесных остатков в этом исследовании. Это говорит о том, что тест L-box является практической альтернативой для оценки реологических параметров потоков мусора, содержащих более крупные древесные остатки.

Ключевые слова: *Реологические параметры, суспензии древесного мусора, модель Бингхема, L-box тест*

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Introduction

In forested catchments affected by wildfires, large volumes of woody debris are frequently introduced into drainage channels, altering the flow characteristics and increasing flow mobility [*Kean et al., 2011*]. Understanding debris-flow behavior requires accurate characterization of its rheology, the relationship between applied stress and deformation especially for complex, heterogeneous mixtures. Rheology is a science that deals with the study of fluid and deformation behavior of fluid. The rheological behaviors of sediment-slurry mixtures are depended on sediment concentration, sediment type, and particle size distribution. Many researchers have shown that the high concentration slurry mixture could be treated as a Bingham fluid having yield stress and viscosity parameters [*Iverson, 2003; Jan et al., 2009, 2011, & 2018; Major & Iverson, 1999*]. The researchers have been suggested numerous techniques to measure the rheology of concrete, concentrated suspensions, thickened tailings and paste fill, which behave as viscoplastic fluids [*Bird et al., 1983; Utracki, 1988; Nguyen & Boger, 1992; Schramm, 2000*]. Nguyen & Boger [*1992*] mentioned two main methods of rheology measurements; namely direct and indirect methods. In the indirect methods, yield stress can be obtained from the shear stress vs. shear rate graph by extrapolating and in the direct methods the yield stress can be obtained under static conditions (which is also known as true yield stress). Specifically, the slump test has been applied as the indirect method to estimate the rheological parameters of the mixtures with coarser particles by identifying the correlations between rheological parameters and slump-spread parameters from the slump test [*Jan et al., 2009, 2011, 2018*].

Building on this framework, the present study investigates the rheological properties of woody-debris suspensions using a rotational rheometer and compares the results with flow characteristics derived from L-box tests. This study has two main objectives: first, to investigate the influences of woody debris on rheological properties of woody-debris suspensions; and second, to find the correlation between the rheological parameters and L-box test parameters, so as to evaluate the potential of using L-box test to assess the rheological parameters.

Materials

In this study, woody-debris suspensions were prepared by combining a fine-sediment suspension (C_{vf} = 0.30) with various sizes (S_w = 5, 10, 15, and 20 mm) and proportions (C_{vg} = 0.00, 0.05, 0.10, 0.15, 0.20, and 0.25) of woody debris (Table 1). The fine-sediment suspension was a concentrated clay-silt-water mixture, formed by mixing volumes of fine sediment (V_f) and tap water (V_w) as:

$$C_{vf} = \frac{V_f}{V_f + V_w} \tag{1}$$

The fine sediment, sourced from reservoir deposits, was cleaned, dried, and free of organic matter. Its particle size distribution (Fig. 1a) had a median diameter (D_{50}) of 0.0036 mm and a density of 2.65 g/cm³ [*Dey et al., 2021*].

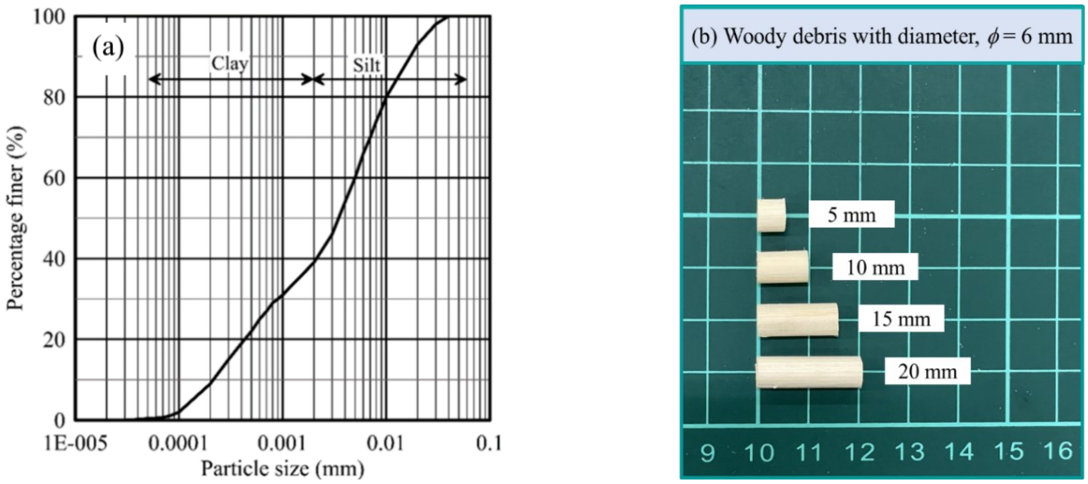

Fig. 1. Size distribution of particles within the fine-sediment suspension (a) and woody debris attributes in present experiments (b)

Woody-debris suspensions were created by mixing a volume (V_g) of woody debris (6 mm diameter; lengths of 5, 10, 15, and 20 mm; Fig. 1b) with a fine-sediment suspension (V_f+V_w) to achieve a woody debris proportion (C_{vg}). The corresponding debris densities were 0.36, 0.34, 0.33, and 0.32 g/cm³ for the respective lengths.

$$C_{vg} = \frac{V_g}{V_g + V_f + V_w}. \tag{2}$$

A woody-debris suspension, containing fine sediment and woody debris, has a total sediment fraction of C_{vt}:

$$C_{vt} = \frac{V_f + V_g}{V_g + V_f + V_w} \tag{3}$$

Table 1. Woody-debris suspensions and their corresponding sample numbers used in the present study

Woody-debris suspensions with a base fine-sediment fraction, C_{vf} = 0.30						
Proportion of woody debris, C_{vg}	0.00	0.05	0.10	0.15	0.20	0.25
Total sediment concentrations, C_{vt}	0.30	0.335	0.37	0.405	0.44	0.475
Sample No. for various sizes, S_w						
5 mm	W-0	W5-1	W5-2	W5-3	W5-4	W5-5
10 mm	W-0	W10-1	W10-2	W10-3	W10-4	W10-5
15 mm	W-0	W15-1	W15-2	W15-3	W15-4	W15-5
20 mm	W-0	W20-1	W20-2	W20-3	W20-4	W20-5

Methodology

In the present study, the experiments were conducted in two phases: firstly, woody-debris suspensions were used as the tested material, and a traditional rheometer was used to measure its rheology. In the second stage, the same suspension was used as the testing materials and its flow behavior were measured by a L-box instead of a rheometer. The Bingham fluid model, having two parameters (i.e., the yield stress and viscosity), was used to simulate the rheological behavior of woody-debris suspensions:

$$\tau = \tau_B + \mu_B \dot{\gamma}, \quad (4)$$

where τ is shear stress (Pa), τ_B is Bingham yield stress (Pa), μ_B is Bingham viscosity (Pa·s), and $\dot{\gamma}$ is shear rate (s^{-1}). The rheological curves of woody-debris suspensions were measured using the "Brookfield DV-III rheometer" and were shown in Fig. 2. The slope of each trend line in the shear stress versus shear rate plot represents the viscosity coefficient. Subsequently, the rheological parameters will be compared with the slump and spread measurements obtained from the L-box tests to identify potential correlations.

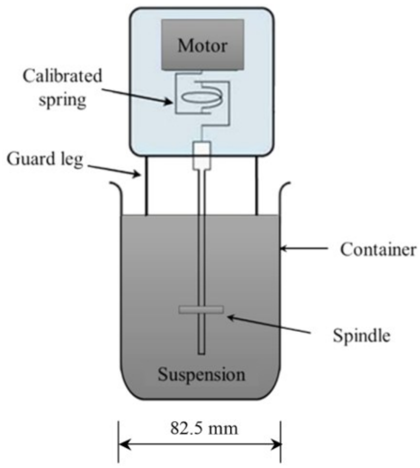

Fig. 2. Schematic diagrams of rheometer measurement by a Brookfield DV–III rheometer

An L-box apparatus was used to evaluate the flowability and passing ability of woody-debris suspensions. The device comprises a vertical section (H_0 = 0.3 m) connected to a horizontal channel (L_0 = 0.7 m), separated by a sliding gate. The vertical section was filled with suspension, and upon lifting the gate, the mixture flowed into the horizontal section. The slump height (H_f) and flow length (L_f) difference were measured to assess flow behavior under various slurry conditions. The experimental setup is illustrated in Fig. 3. To evaluate the flow behavior of the tested suspensions, the final slump height and flow length were normalized by the initial sample height (corresponds to the height of the vertical section H_0). These normalized parameters are referred to as the flow height ratio (H_r) and the spread ratio (L_r), and are defined in eqs. (5) & (6):

$$H_r = H_f / H_0, \tag{5}$$

$$L_r = L_f / H_0. \tag{6}$$

Based on the calculated H_r and L_r values, the relationships between the rheological properties (e.g. yield stress and viscosity) and the flow behavior (e.g. flow height ratio and spread ratio) were analyzed. By comparing the experimental results of the rheological parameters and the L-box test parameters to assess their correlations.

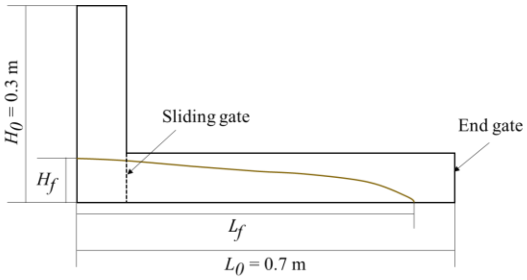

Fig. 3. Schematic diagrams of a L-box test setup

Results

Rheological parameters of woody-debris suspensions

As illustrated in Fig. 4, a linear relationship between shear stress and shear rate is evident, indicating that the suspensions examined in this study exhibit Bingham fluid behavior. For a fine-sediment fraction C_{vf} of 0.30 without woody debris (C_{vg} = 0.00), the shear rate does not exceed 20 s^{-1}, and the corresponding shear stress ranges from approximately 12.4 to 18.1 Pa. When woody debris is present, the shear stress increases with the proportion of woody debris. Specifically, at C_{vg} of 0.05, 0.10, 0.15, 0.20, and 0.25, the shear stress ranges are 14.2~20.3 Pa, 16.1~22.9 Pa, 18.1~26.0 Pa, 20.3~29.6 Pa, and 22.6~34.2 Pa, respectively, as also depicted in Fig. 4.

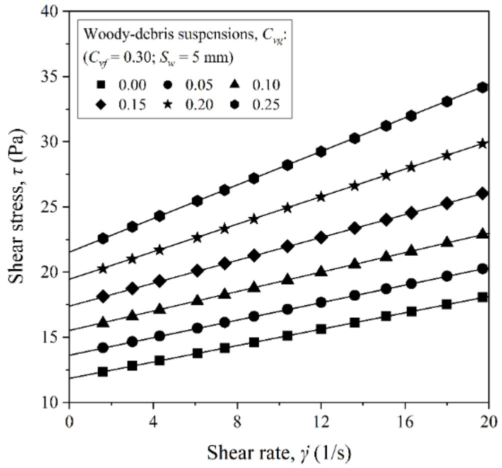

Fig. 4. Rheological relations of woody-debris suspensions with different C_{vg} under the same C_{vf} of 0.30 and S_w = 5 mm

To further illustrate the Bingham fluid model, Fig. 5 displays that the mean values of the rheological parameters, Bingham yield stress (τ_B) and viscosity (μ_B), of the woody-debris suspensions increase as woody debris proportion (C_{vg}) increases and woody debris size (S_w) decreases. Specifically, increasing the woody debris proportion enhances internal friction and structural rigidity within the suspension, resulting in higher yield stress as more force is required to initiate flow (Fig. 5a). The presence of woody debris also contributes to greater energy dissipation, thereby increasing the viscosity, or resistance to shear deformation [*Major & Iverson, 1999; Berger et al., 2011; Matioli et al., 2013*]. Conversely, increasing woody debris size at a constant volume fraction reduces the number of particles and their interparticle interactions, weakening mechanical interlocking. This leads to a decline in both yield stress and viscosity (Fig. 5b). In addition, larger particles interact less with the fluid due to their lower surface area-to-volume ratio, further reducing internal resistance to flow [*Iverson, 1997; Matioli et al., 2013*].

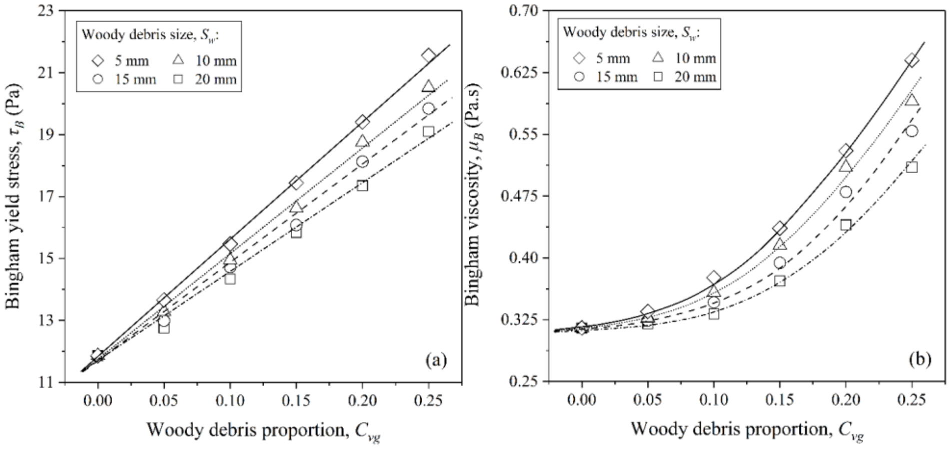

Fig. 5. The effects of woody debris proportions and sizes on the rheological parameters of woody-debris suspensions with C_{vf} of 0.30

L-box test

The flow height ratios and spread ratios from the L-box tests under various conditions are presented in Fig. 6. As shown in Fig. 6a, the flow height ratio slightly increases with higher woody debris proportions and smaller particle sizes, while lower proportions combined with larger sizes lead to a decrease. Conversely, the spread ratio exhibits an opposite trend, greater values are observed with lower woody debris proportions and larger sizes, whereas higher proportions of larger woody debris slightly reduce the spread ratio (Fig. 6b). These trends suggest that woody debris content and morphology influence the deformation behavior and mobility of the suspensions. The increase in flow height ratio indicates enhanced resistance to flow, while the reduced spread ratio implies lower lateral mobility under more structurally rigid conditions.

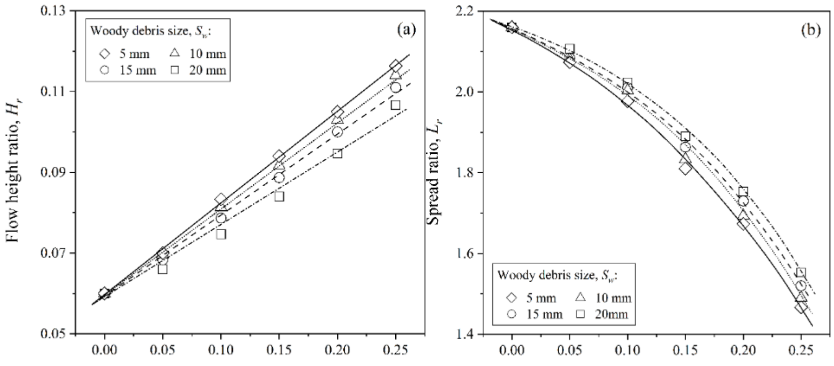

Fig. 6. The effects of woody debris proportions and sizes on the flow height ratio and spread ratio of woody-debris suspensions with C_{vf} of 0.30

Correlations between the rheological parameters and L-box test parameters

The rheological parameters (the yield stress and viscosity) obtained from rheometer measurements, L-box test parameters (flow height ratio and spread ratio) obtained from L-box tests for woody-debris suspensions used in this study were compared as shown in Fig. 7. In the above rheological and L-box test parameters models analysis, the values of R^2 for the relation of parameters of woody-debris suspensions ranges from 0.95 to 0.99. The R^2 values greater than 0.7 are considered as strongly correlated [*Cohen et al., 2003*], as a result it implies that the rheological parameters are strongly related to L-box test parameters.

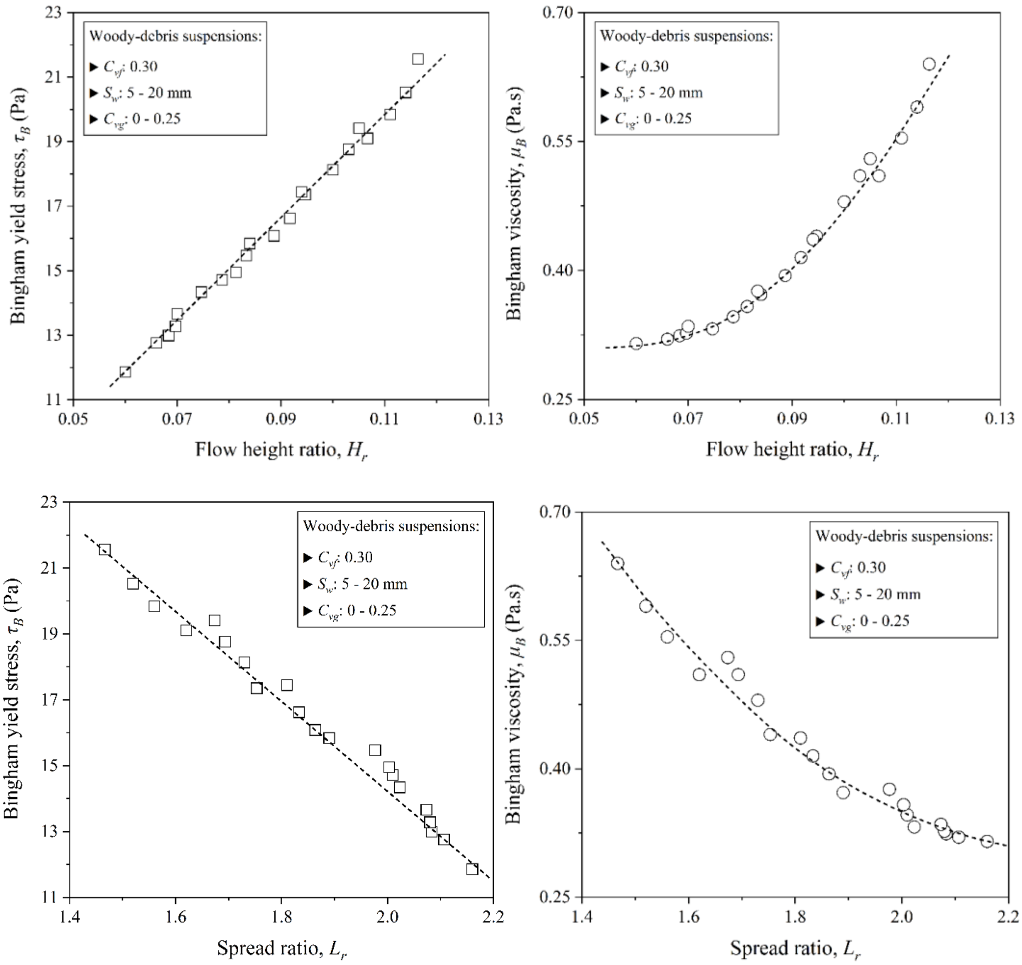

Fig. 7. Correlations between the rheological parameters and L-box test parameters of woody-debris suspensions

Table 2. The correlations between the rheological parameters and L-box test parameters of woody-debris suspensions

Correlation model	Coefficients of model		Coefficient of determination, R^2
	a	b	
$\tau_B = aH_R + b$	162.45	2.03	0.99
$\mu_B = ae^{bH_R}$	0.14	12.03	0.95
$\tau_B = aL_R + b$	-13.49	41.36	0.98
$\mu_B = aL_R^{\ b}$	1.29	-1.86	0.98

Conclusions

This study conducted rheological experiments and L-box tests of woody-debris suspensions that have Bingham fluid behavior, to explore the correlation between the rheological parameters and L-box test parameters. The key findings and conclusions of this study are summarized as follows:

1. The woody-debris suspensions at low shear rates (< 20 s^{-1}) exhibit the characteristics of Bingham fluid.
2. The rheological parameters, including yield stress and Bingham viscosity, are influenced by both the proportion and size of woody debris. Generally, larger woody debris combined with higher proportions lead to increased values of these parameters.
3. Higher woody debris proportions and smaller sizes tend to increase flow height ratio, while lower proportions and larger sizes promote greater lateral spread ratio.
4. The rheological parameters show a strong correlation with L-box test parameters, highlighting the potential of using L-box test as an indirect method for estimating the rheological parameters of concentrated debris flows containing the large woody debris.

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