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Submarine Landslides: Effects of Seafloor Roughness and Flow Velocity on Pipeline Impact Loads

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ABSTRACT: This study investigates the impact forces generated by submarine debris flows on subsea pipelines using geotechnical centrifuge modeling. The main objective was to analyze how variations in debris flow velocity influence pipeline loading. Landslide velocity was controlled by applying sandpapers with different roughness grades to the slope surface. Flow velocity was measured using ramp-mounted instrumentation synchronized with high-speed video recordings. Prior to each experiment, T-bar penetration tests were conducted to determine the undrained shear strength (Su) of the mud, using a dedicated compartment filled with mud identical to the material prepared for the landslide. Pipeline impact forces were quantified through strain gauges installed on calibrated support rods. The experimental results demonstrated a strong relationship between flow velocity, flow morphology, and the resulting impact forces on pipelines. The findings agree with trends reported in the literature and emphasize the need to account for substrate roughness and debris flow velocity in risk assessment and the design of subsea infrastructure, improving the safety and reliability of submarine pipeline systems.

1 INTRODUCTION

Submarine mud flows exhibit distinct behaviors compared to subaerial flows and represent a major hazard to subsea infrastructure. Offshore energy systems, particularly those associated with oil and gas production, are especially vulnerable; failures can result in significant economic, environmental, and social consequences.

Key differences between submarine and terrestrial slopes include the triggering mechanisms and slope angles, which in the marine environment are often extremely gentle Once initiated, submarine debris and mud flows can travel exceptionally long distances, sometimes hundreds of kilometers.

Research on submarine landslides spans oceanography, geology, and civil engineering, with substantial contributions from geotechnics and fluid mechanics. Experimental approaches commonly include both 1g physical modeling and geotechnical centrifuge testing. These studies typically investigate parameters such as debris volume, grain size characteristics, flow velocity, runout distance, impact forces, and the response of subsea structures.

Submarine landslides can inflict severe damage on offshore facilities, mobilizing large sediment volumes and propagating over low-gradient slopes (0.5°-3°) for hundreds of kilometers, with events lasting from hours to days (Locat & Lee, 2002). Long-distance hydrocarbon export pipelines, sometimes exceeding 500km, are particularly exposed to these hazards. They experience hydrodynamic loading from waves and currents, sudden temperature-pressure changes, and direct impact forces from debris flows. Randolph & White (2012) emphasize that pipelines are especially susceptible due to their length, structural vulnerability, and interaction with irregular seabed terrain.

Pipeline assessment approaches include theoretical analyses, physical experiments, and numerical simulations. Theoretical work draws on soil and fluid mechanics principles (Randolph & White, 2012; Sahdi et al., 2014). In deep-water settings, debris flow rheology strongly influences the predictive accuracy of Computational Fluid Dynamics (CFD) and impact force estimation (Gauer et al., 2005; Xiu et al., 2015; Debnath et al., 2018; Liu et al., 2019; Guo et al., 2023).

Geotechnical centrifuge testing provides a powerful means of replicating seabed processes by allowing scaled models to experience prototype-level stresses under elevated gravity fields (Yin et al., 2017). When model dimensions are reduced by a factor N and tested at N-g acceleration, prototype stress-strain behavior can be reproduced (Taylor, 1995). Centrifuge-based studies of submarine debris flows include Chi et al. (2011), Guo et al. (2023), Sahdi et al. (2020), Rui & Yin (2019), Zhang et al. (2019) and Zhang & Askarinejad (2019), and Brazilian contributions by Mota (2016), Pelissaro (2018), Acosta et al. (2017), Santos (2018), Hotta (2019), Ferreira (2020), Fonte Boa et al. (2022), and Melo et al. (2025).

This study investigates the influence of mudflow velocity on the impact loads transmitted to seabed pipelines. Geotechnical centrifuge model tests were carried out in which flow velocity was systematically controlled by varying the slope surface roughness. This methodology enabled a clear assessment of the role of velocity in debris-flow–pipeline interactions. Direct measurements of flow velocity were obtained through dedicated instrumentation, allowing the analysis of hydroplaning behavior governed by effective stress conditions and Reynolds number effects. The results quantify the magnitude of impact forces acting on pipelines and establish clear relationships between flow characteristics and the resulting load literature review

Impact loading on subsea pipelines is typically assessed using geotechnical and hydrodynamic principles, which may be applied separately or in combination (Quian et al., 2020; Guo et al., 2019; Liu et al., 2015; Randolph & White, 2012; Sahdi et al., 2013; Zakeri et al., 2008, 2012). A combined framework accounts for both soil resistance and inertial forces generated by the moving debris-laden fluid. Under this approach, the normal impact force acting on the pipeline, F_n, can be estimated by equation 1:

$$Fn = C_d\left(\frac{1}{2}\rho v^2\right).A + N_H\,.S_{u-op}.A \qquad (1)$$

the first term represents hydrodynamic loading and the second soil-induced forces. In this expression, C_d denotes the drag coefficient, ρ the bulk density of the flow (kg/m^3), ν the flow velocity (m/s), A the projected cross-sectional area of the pipeline (m^2), N_H the bearing capacity factor, and S_{u-op} (kPa) the operative undrained shear strength.

The non-Newtonian Reynolds number, a dimensionless parameter characterizing debris flow dynamics, can be derived from fluid shear stress, together with the bulk density and flow velocity, as defined by Zakery et al. (2008):

$$\mathrm{Re}_{\mathrm{non-Newtonian}} = \frac{\rho v^2}{\tau} \qquad (2)$$

where ρ denotes the bulk density, ν the flow velocity, and τ the shear rate (s^{-1}). Beyond rheological characterization, several researchers employ a geotechnical framework in which soil shear stress τ is associated with undrained shear strength (Su). In this approach, Su is rate-dependent and varies with soil strain rate ν/D, where ν is flow velocity and D the characteristic diameter exposed to the landslide (Randolph & White, 2012; Duta & Hawlader, 2018; Sahdi et al., 2020). The relationship is expressed as:

$$S_{u-op} = S_{u-ref}\left(\frac{v/D}{\dot{\gamma}_{ref}}\right)^{\beta} \qquad (3)$$

Where, $S_{(u-op)}$ is the operative undrained shear strength (kPa), $S_{\_(u-ref)}$ the reference undrained shear strength (kPa) at the reference strain rate $\dot{\gamma}_{ref}$ (s^{-1}), and β a rate-sensitivity exponent, analogous to the power-law in non-Newtonian rheology. Jeong et. al. (2009) reported β values ranging from 0.05 to 0.17 for clayey soils with differing origins and properties. When both considered, Sahdi et al., (2013) demonstrated that flows with non-Newtonian Reynolds numbers > 3 impose predominantly hydrodynamic loads on pipelines. Dutta and Hawlader (2018) further showed that geotechnical effects dominate only when this number is below 0.5. For low-strength mixtures ($R_{e\ \text{non-Newtonian}}$ > 3), hydrodynamic forces alone provide a reliable estimation of impact loads, expressed by:

$$Fn = C_d\left(\frac{1}{2}\rho v^2\right).A \qquad (4)$$

2 MATERIALS AND METHODS

Experiments were conducted in the geotechnical centrifuge at the UENF campus using reduced-scale physical models. The prototype-to-model scale ratio was 1:56, corresponding to a testing acceleration of 56g.

A schematic overview of the centrifuge setup is presented in Figure 1. An acrylic ramp with a gentle 3° slope simulated the seabed surface, linking the release gate to the pipeline. Lateral acrylic guide plates were installed to direct the debris flow toward the center of the pipeline. The slide impacted the pipeline at a 90° angle, and in all experiments, the pipeline was positioned at the ramp outlet with half of its diameter exposed. A wave absorber installed at the right boundary of the container prevented wave reflection toward the impact area. The container comprised two compartments (top view). The upper compartment (Box 2) housed the mud box used exclusively for in-flight mini T-bar testing (bar diameter: 6.96 mm; length: 28.11 mm), enabling measurement of undrained shear strength during the centrifuge run. Both mud boxes were filled with the same mud volume, totaling 7.1 m³. The lower compartment (Box 1) contained the mud reservoir, sliding ramp, instrumentation, flow channel, pipeline, and a wave-dissipating wall to prevent flow return. Three paired pore pressure and total stress transducers were embedded along the ramp surface to monitor effective stress evolution during flow passage, supporting assessment of hydroplaning conditions. A high-frequency data acquisition system (100 kHz) and a high-speed camera operating at 550 fps were employed in all tests to record flow morphology and compute debris flow velocity throughout the event.

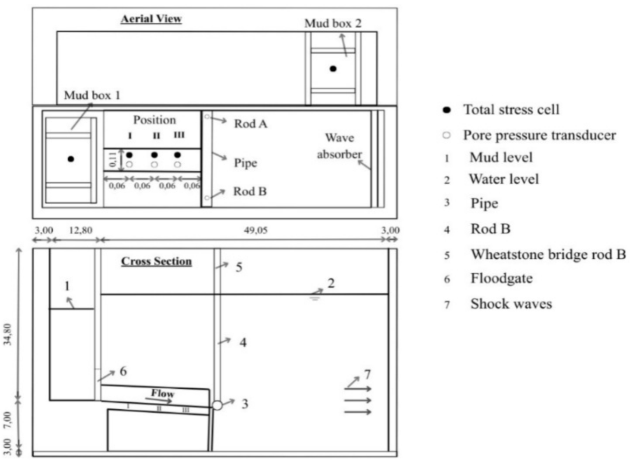

Figure 1. Schematic of the centrifuge test setup.

Flow velocity was controlled by modifying the roughness of the ramp surface (Figure 2). Sandpaper sheets were bonded across the entire ramp to generate surfaces with different roughness levels. Table 1 summarizes the roughness properties used. Average surface roughness was measured using a laser confocal microscope and a custom scanning device equipped with laser displacement sensors.

The model pipeline consisted of an aluminum tube with an external diameter of 25.5 mm and a wall thickness of 1.9 mm. The pipeline was fixed to two support rods at its ends, instrumented with strain gauges to measure force at the moment of impact.

The rheological behavior of the mud was characterized using an RST-CC-SST Brookfield rheometer under controlled temperature and shear-rate conditions, allowing precise characterization of the material's rheological behavior. The resulting flow curve is expressed in Equation 5, indicating Bingham-type behavior with an apparent yield stress of 269.09 Pa and a plastic viscosity of 7.2162 Pa·s.

$$\tau = 269.09 + 7.2162\,.\dot{\gamma} \quad (5)$$

3 RESULTS

Total stress cells readings confirmed that all tests began under comparable initial conditions. Likewise, undrained shear strength values from the T-bar tests were consistent across runs; therefore, a single operative undrained shear strength value was adopted for analysis. The mixture exhibited $S_{u-op} = 0.26$kPa. Operative undrained strength values were then adjusted using $\beta = 0.05$.

Table 1. Properties of sliding surfaces.

Test	Surface material	Average roughness (μm)	Grain size (mm)
1	Acrylic	0.13	-
2	Sandpaper 80	15.50	0.20
3	Sandpaper 36	30.42	0.53
4	Sandpaper 16	85.22	1.32

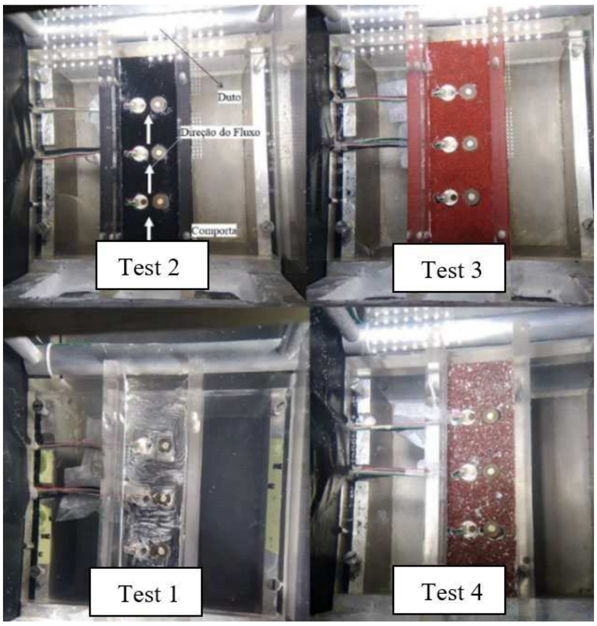

Figure 2. Acrylic ramps with applied roughness layers.

Table 2 summarizes measured front-velocity values. Average velocity was computed over the 5 cm distance between sensor pairs TT2/PP2 and TT3/PP3, selected to avoid the highly turbulent, irregular zone near the release gate. Increasing ramp roughness reduced flow velocity; the smoothest sandpaper surface reduced velocity by approximately 20% relative to the acrylic surface (Figure 3). Velocity differences among the sandpaper cases were smaller. Surface roughness also affected flow morphology due to increased solid particle interaction.

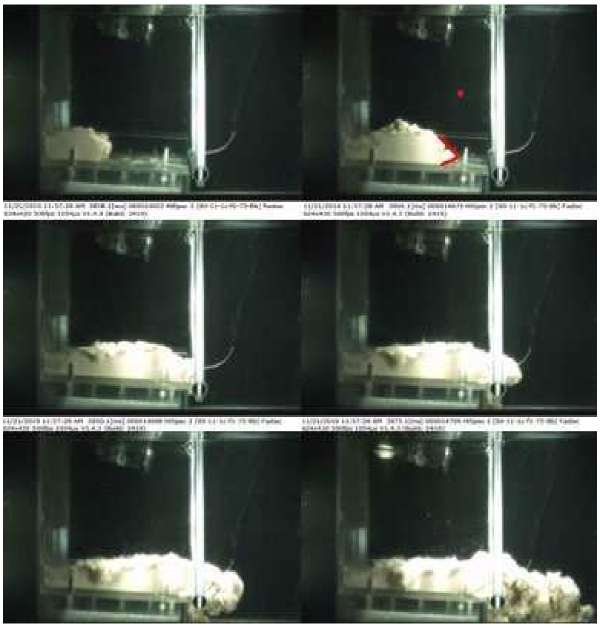

Figure 4. Sequence of debris-flow impact event.

Table 2. Mean flow-front velocity.

Test	Δs (m)	Δt (s)	v_m(m/s)
1	0.05	0.035	1.429
2	0.05	0.044	1.142
3	0.05	0.046	1.090
4	0.05	0.051	0.984

Table 3 lists the maximum forces recorded by each instrumented support rod and the resulting total impact force on the pipeline.

Table 3. Pipeline impact force results.

Test	Impact Force(N)		
	Rod A	Rod B	Total
1	4.142	3.782	7.924
2	3.062	2.862	5.924
3	2.782	2.532	5.314
4	2.602	2.355	4.957

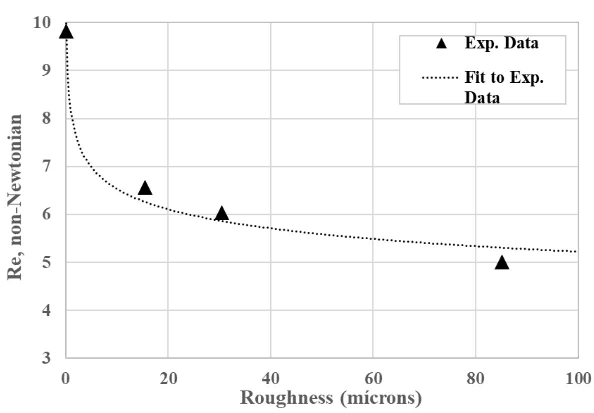

Figure 3. Relationship between non-Newtonian Reynolds number and ramp roughness.

Figure 4 illustrates a sequence from Test 1, showing hydroplaning in the second frame followed by impact on the pipeline.

The total impact force measured by the instrumented rods was used to calculate the drag coefficient C_d. The non-Newtonian Reynolds number was also computed using the rheological model (Equation 2).

To investigate the relationship between impact loading and flow velocity, the measured forces were normalized by the exposed pipeline area and the shear stress defined in Eq. (5) (Figure 5). As anticipated, the impact forces increased with increasing debris-flow velocity, in agreement with the theoretical trend predicted by Eq. (4). This formulation, derived within a purely hydrodynamic framework, is applicable to low-strength mixtures and to flows characterized by non-Newtonian Reynolds numbers greater than 3 — conditions that were verified in the present experimental program (Figure 3).

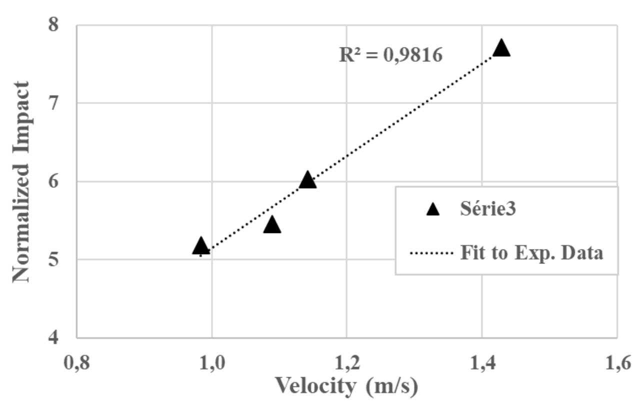

Figure 5. Normalized impact forces as a function of velocity.

4 CONCLUSIONS

The experimental program provided a comprehensive assessment of debris flow behavior under varying surface roughness conditions, demonstrating the direct effect of roughness on flow velocity and associated impact forces on pipelines. Consistent mud properties, verified through T-bar testing, ensured experimental repeatability and supported the use of a single operative undrained shear strength value $S_{u-op} = 0.26$ kPa across all tests. In all cases, the non-Newtonian Reynolds number exceeded 3, indicating turbulent flow dominated by inertial forces.

Increasing surface roughness led to reduced mean flow velocity, confirming enhanced dissipation of kinetic energy due to friction and influencing both flow dynamics and front morphology. The proportional relationship between flow velocity and normalized impact force, consistent with the hydrodynamic expression, further supports the validity of the theoretical framework applied. Overall, the results emphasize the importance of accurately characterizing the sliding surface and employing high-resolution instrumentation in experimental investigations of non-Newtonian debris-flow behavior, particularly in low-strength, highly mobile systems relevant to offshore geotechnical engineering.

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