Development of a Submarine Gravity Flow Modelling Device in a Beam Centrifuge

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ABSTRACT: Submarine gravity flows, among Earth's largest landslide events, play a vital role in sediment transport and submarine geological evolution while posing significant risks to offshore infrastructures. This study presents a novel centrifuge device capable of simulating the transportation of gravity flows and their erosion effects on seabed sediments. Serving as the pre-research device of the "Wave, Tsunami, and Gravity Flow Modelling Device" within China's major scientific and technological infrastructure facility "Centrifugal Hypergravity and Interdisciplinary Experiment Facility (CHIEF)", it incorporates a double-gate release system for the rapid discharge of gravity flow slurry. Scaling laws governing flow dynamics and seabed erosion were summarised. A multiphase numerical model was established to validate the scaling laws and investigate the modelled flow velocity, and flow regime, etc. Validation tests under both normal gravity and hypergravity conditions were conducted. The responses of pore pressure and soil pressure in the seabed were experimentally investigated, and the observed flow characteristics showed good agreement with numerical simulations. This device proves effective in modelling gravity flows with key parameters, i.e., velocity and height of flow head, comparable to those observed in the field.

1 INTRODUCTION

Submarine gravity flows are critical for sediment transport and the evolution of submarine geology, and pose significant threats to offshore infrastructure (Talling et al., 2013). The erosion effect has been noted to play an important role in the growth of the flow volume, causing it to grow by up to three times (Nugraha et al., 2022). Understanding the processes underlying seabed erosion during gravity flows is therefore essential for accurately estimating flow dynamics and evaluating the geological impacts of these events.

Numerous laboratory studies have been conducted to investigate flow patterns (Ilstad et al., 2004a; Zhou et al., 2025; Mohrig and Marr, 2003), the hydroplaning phenomenon (Ilstad et al., 2004b; Mohrig et al., 1998), and interactions with seabed structures (Sørlie et al., 2023; Zakeri et al., 2008), etc. Centrifuge modelling can replicate the in-situ stress field at a model scale, offering a more refined method for studying gravity flow behaviour (Acosta et al., 2017; Gue, 2012; Hotta et al., 2020; Yin et al., 2019). However, most existing studies employ a rigid seabed boundary, leaving the response of the seabed itself largely unexplored. An exception is that Du et al. (2022a, b) employed 1g tests to study erosion behaviours and demonstrated the influence of seabed properties on flow mobility.

To fill the existing gaps, this paper presents a novel centrifuge device designed to simulate the interaction between submarine gravity flow and the erodible seabed. Scaling laws governing flow dynamics and seabed erosion were summarised. A multiphase numerical model was established to validate the scaling laws and investigate the modelled flow behaviours. Validation tests under both normal gravity and hypergravity conditions were conducted to demonstrate the device's performance.

2 DEVELOPMENT OF A SUBMARINE GRAVITY FLOW SIMULATING DEVICE

2.1 Scaling laws

Regarding the erosion process, the governing factor of the driving stress is the shear stress at the flow-bed interface τ_f (Haas et al., 2022), and the resistance against erosion is the shear strength of seabed τ_{be}. A term called the erosion rate (E_r), previously used in subaerial debris flow studies (Iverson, 2012), is employed to assess seabed erosion under gravity flow. A diagram illustrating the calculation of E_r is shown in Fig. 1, and E_r can be expressed as (Chen et al., 2026):

$$E_r = \frac{h_{be}}{\Delta t_e} = \frac{\tau_f - \tau_{be}}{v_{fb}\rho_b} \quad (1)$$

The similitude relating to τ_f, τ_{be}, and E_r can be unconditionally satisfied by applying established scaling laws for centrifuge modelling (Taylor, 1995). To appropriately match both inertial and diffusional time scales, a pore fluid with a viscosity N times that of water should be employed.

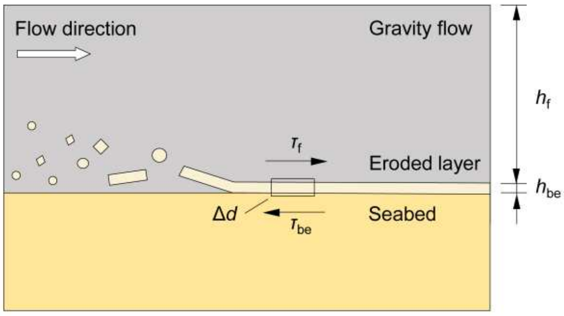
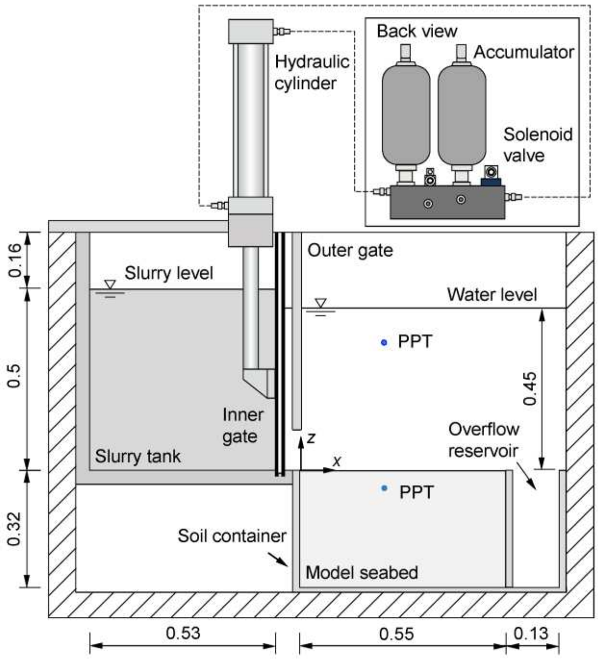


Figure 1. Schematic diagram for seabed erosion rate calculation (Chen et al., 2026).

Regarding flow dynamics, gravity flows are commonly modelled as homogeneous non-Newtonian fluids. Three dimensionless parameters should be matched: the dimensionless yield stress τ_y^* (Mohrig et al., 2003), the densimetric Froude number Fr_d, and the Reynolds number $N_{R(H\text{-}B)}$ (Elverhoi et al., 2010). In centrifuge modelling, Fr_d and τ_y^* can be reliably satisfied by properly scaling the model geometry and the acceleration level. However, satisfying the $N_{R(H\text{-}B)}$ similarity criterion remains challenging. A typical practice is to ensure that $N_{R(H\text{-}B)}$ remains below the turbulence threshold (Leeuw et al., 2016).

2.2 Gravity flow simulating device

The in-flight gravity flow simulating device (Fig. 2) is a preliminary prototype for the "Wave, tsunami and gravity flow modelling apparatus" within the China's Major Sci-Tech Infrastructure Project, the "Centrifugal Hypergravity and Interdisciplinary Experiment Facility (CHIEF)". The device includes a strong box, a model seabed container, a slurry tank and a double-gate triggering module. The outer gate is fixed at a predetermined position before tests, whereas the inner gate is rapidly lifted by a hydraulic cylinder to initiate a dam-break-style slurry release (Acosta et al., 2017). At 100g, the inner gate can be fully raised within 0.3 seconds. The rapid gate lift is achieved through a high-performance hydraulic system, providing over 100 kN of lifting force. The inner gate is made of aluminium alloy to minimise its weight, and its surfaces are coated with polytetrafluoroethylene (PTFE) to reduce friction during actuation.



(a)

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Figure 2. Submarine gravity flow simulating device: (a) schematic diagram (dimensions in m); (b) photograph of device.

A computational fluid dynamics (CFD) model was adopted to validate the scaling laws of flow dynamics. The model-scale simulation was conducted under 100*g*. A rigid bottom boundary was used without considering seabed deformation. The prototype-scale simulation was performed under 1*g* conditions, with its geometry scaled up by a factor of 100. The parameters for the gravity flow were determined using the scaling laws specified in Section 2.1. Figure 3 compares the seabed shear stresses obtained from the 1*g* and 100*g* simulations at different time instances. Good agreements can be seen. Furthermore, the flow patterns also showed good consistency, though these results are not presented here for length limit.

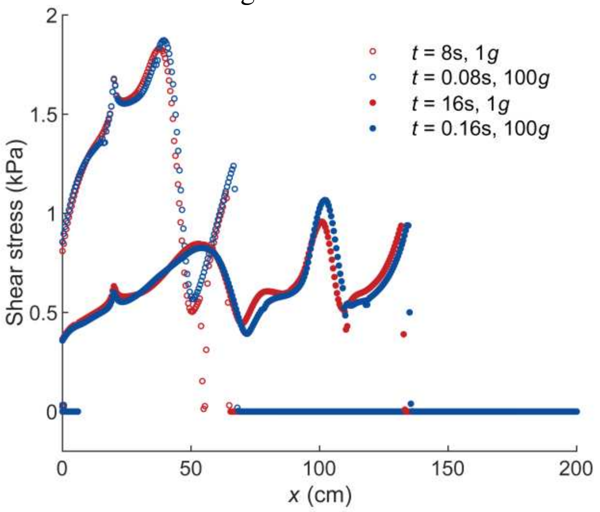

Figure 3. Comparison of basal shear stress of 1g and 100g simulations.

The influence of gate opening height (H_{gate}) on the flow dynamics was further investigated at 100g. Figure 4 illustrates the flow patterns and velocity distributions at different time instances. The gravity flow developed a "head-shaped" flow front upon release, with a flow body of lower height behind it. The vertical velocity profile showed an initial increase followed by a decrease from the bottom to the top. Figure 5 shows the evolution of the flow height. The flow height in H_{gate} = 0.3m generally exhibited a decreasing trend. In contrast, the flow height gradually increases in the case of H_{gate} = 0.1m.

Figure 6 illustrates the evolution of the horizontal flow velocity at different positions. Upon the arrival of the gravity flow, the horizontal flow velocity increased rapidly to a peak value before gradually decreasing. The peak velocities for H_{gate} = 0.3m were lower than those for H_{gate} = 0.1m at all measured points. In addition, the velocity decreasing rate for H_{gate} = 0.1m was slower than that for H_{gate} = 0.3m. The post-peak velocities for H_{gate} = 0.1m exhibited less variation among the different measurement points, indicating a more uniform horizontal distribution.

This study focuses on developing a novel centrifuge device for simulating the interaction between submarine gravity flow and the erodible seabed. Validation tests introduced in the following sections show that the flow patterns and the seabed response can be well modelled within the controlled centrifuge space. It should be noted, however, that the short flow travel distance limits its application in simulating long-term run-out behaviour and full flow evolution.

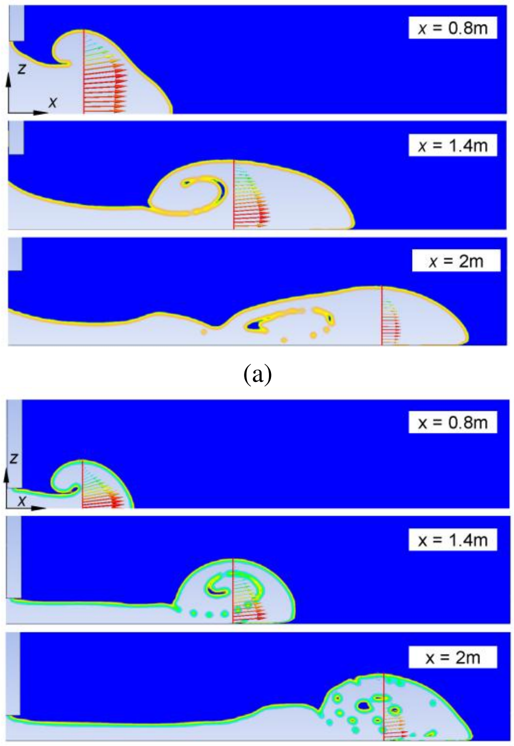

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Figure 4. Flow patterns and vertical flow velocity profile for different gate opening height: (a) H_{gate} = 0.3m; (b) H_{gate} = 0.1m.

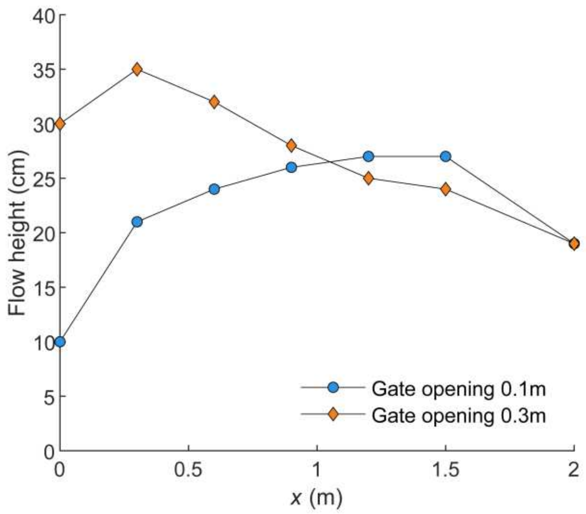
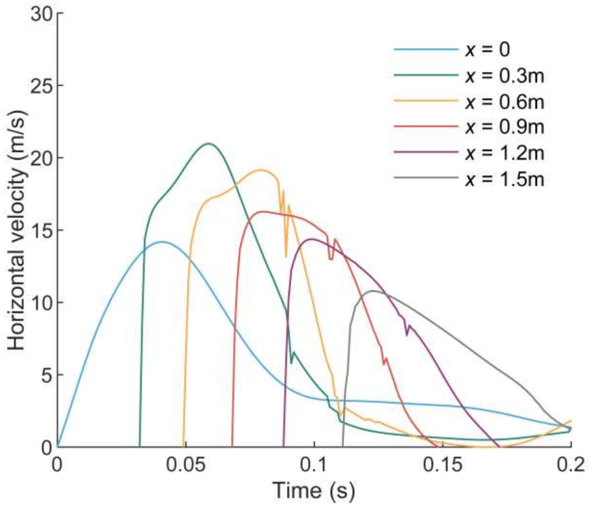


Figure 5. Time-variation of flow height for different gate opening height.



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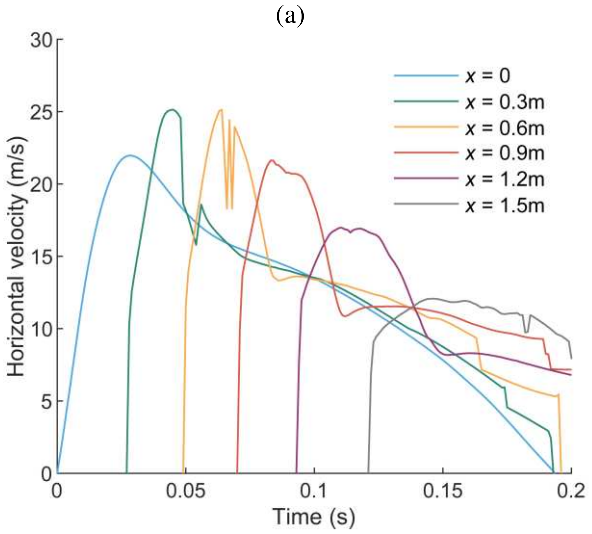

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Figure 6. Evolution of the horizontal flow velocity at different positions: (a) H_{gate} = 0.3m, measured at z = 0.1m; (b) H_{gate} = 0.1m, measured at z = 0.06m.

3 DEVICE PERFORMANCE IN NORMAL GRAVITY AND CENTRIFUGE TEST

3.1 Normal gravity test

3.1.1 Experimental set-up

ISO standard sand was used to prepare the model seabed by gently pouring the sand into water. The final relative density of the sand was 60.9%. The component of gravity flow slurry was 20% Malaysian kaolin clay (Goh, 2003), 45% ISO standard sand and 35% water (in mass fraction). The slurry height was 0.55 m, the water level was 0.35m, and the opening of the outer gate was set to 13 cm. A camera was used to capture the flow pattern. The excess pore pressure (EPP) was monitored using pore pressure transducer (PPT) embedded at a depth of 5 cm. During the release of the gravity flow, changes in liquid surface elevation were monitored with PPT installed on a frame near the initial water surface.

3.1.2 Test results

Following the quick lifting of the inner gate, the gravity flow front accelerated from the initial condition. Figure 7 reveals that the frontal velocity remained nearly constant as it passed over the seabed, at an average velocity of 1 m/s. The experimental curve aligns well with companion Computational Fluid Dynamics (CFD) simulation, in which the problem was simplified to two dimensions, and the erodible seabed was replaced with a no-slip wall boundary. The flow properties were referenced from Zakeri et al. (2008), where a same slurry component was adopted. Figure 8 reveals that a "head-shaped" front formed after gate opening, which was observed in both the experimental test and the numerical model.

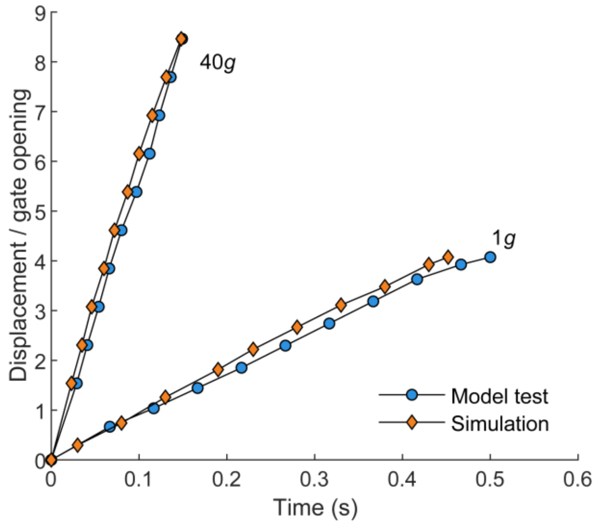


Figure 7. Time-variation of normalised flow frontal displacement in normal gravity and centrifuge test.

Figure 9(a) shows the time-variation of excess pore pressure ($\Delta P_{w\text{-}1g}$) induced by the gravity flow and the pressure increment ($\Delta P_{0\text{-}1g}$) induced by the changes in water level. The excess pore pressure exhibited an immediate rise upon the release of gravity flow. This observation highlights the strong EPP response prior to the arrival of the flow front. After reaching its peak, $\Delta P_{w\text{-}1g}$ decreased to a stabilised value. Figure 9(b) shows the averaged seabed erosion depth at different cross-sections, obtained by measuring the seabed elevation after test. The average erosion depth in the whole model seabed was 2.7mm.

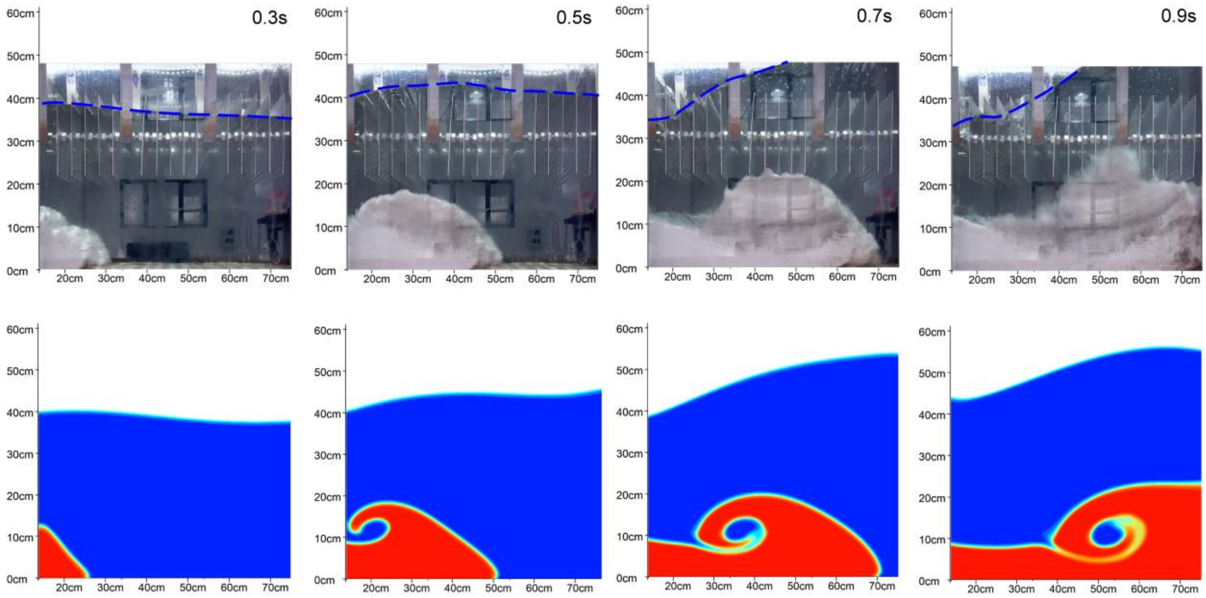
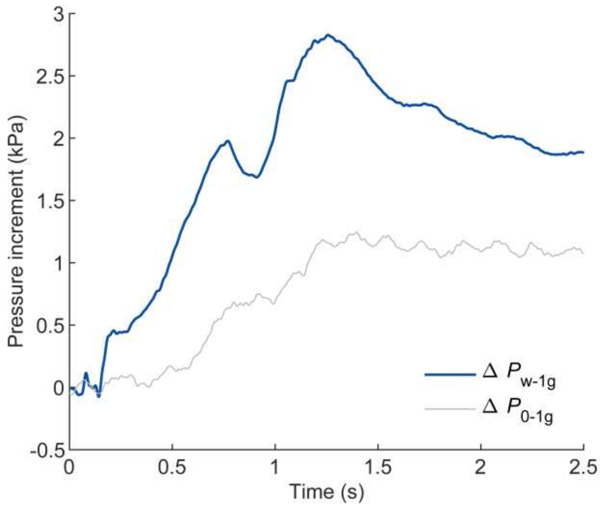


Figure 8. Flow patterns in present normal gravity test and companion numerical simulation.



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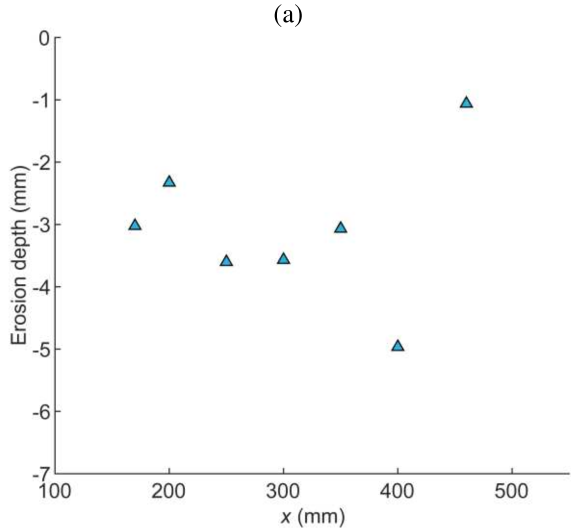


(b)

Figure 9. Time-variation of pore pressure increment and seabed erosion depth: (a) pore pressure increment; (b) averaged seabed erosion depth at different sections.

3.2 Centrifuge test

3.2.1 Experimental set-up

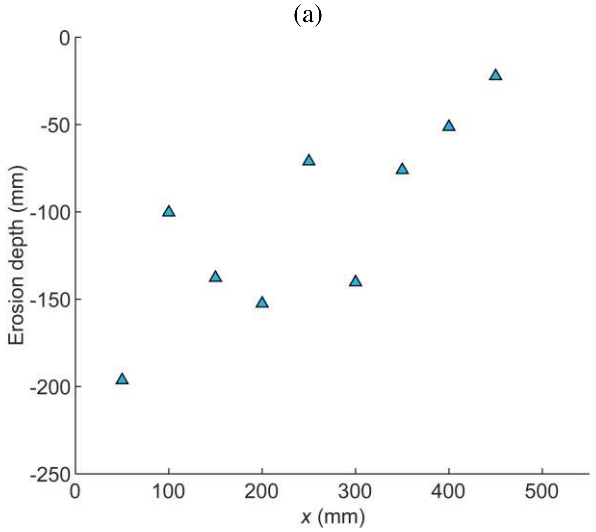
The model seabed was prepared by gently pouring Fujian sand into a sodium carboxymethyl cellulose (CMC-Na) solution, achieving a final relative density of 38.3%. The gravity flow slurry was made of Malaysian kaolin clay at a water content of 120%, with a density of 1334 kg/m^3. Rheological testing indicated that its shear response follows the Herschel–Bulkley model, expressed as $\tau = 173 + 400\dot{\gamma}^{0.11}$. The test was performed on the ZJU400 beam centrifuge at Zhejiang University, China (Chen et al., 2010). The initial setup featured a CMC-Na solution with a liquid level 0.45 m above the model seabed, and the slurry with a height of 0.5 m. The outer gate opening was fixed at 6.5 cm. Flow dynamics and seabed deformation were recorded using a high-speed camera throughout the experiment, which was conducted under a centrifugal acceleration of 40g.

3.2.2 Tests results

Figure 7 reveals that the flow front passed over the seabed at a nearly constant average velocity of 3.64 m/s, which closely matches the results from the companion CFD simulation. The corresponding densimetric Froude number calculated from this experiment is 0.85, exceeding the proposed threshold of 0.35 (Mohrig et al., 1998) for the onset of hydroplaning. Indeed, occurrence of hydroplaning is observed by the lifting of the frontal head. The maximum flow height reaches 5.6m (in prototype scale). This device effectively models gravity flows, with key parameters, i.e., velocity and height of flow head, comparable to field observations.

The erosion depth was determined by interpolating the post-test seabed elevation. Figure 10(a) presents a representative post-test seabed cross-section, while Figure 10(b) shows the average erosion depth across different sections. Despite the relatively short travel distance modelled in the experiment, the average prototype erosion depth reached 9.8 cm, corresponding to an erosion rate of 18.4 mm/s. More details about this test can be found in Chen et al. (2026).

(a)



(b)

Figure 10. Seabed erosion behaviour: (a) representative seabed cross-section after test; (b) averaged seabed erosion depth at different sections (in prototype scale).

4 SUMMARY

This study presents the development of a centrifuge device for modelling the gravity flows and their interaction with the seabed. Device performance was experimentally investigated using example experiment conducted under both normal gravity and hyper-gravity conditions.

Scaling laws governing both flow dynamics and the erosion process in centrifuge tests were summarised. Good agreement in seabed shear stress between 1*g* and 100*g* conditions was demonstrated in numerical simulations through the application of the scaling laws in flow dynamics. The vertical flow velocity profile exhibited a pattern of initial increase followed by a decrease with height. A smaller gate opening was found to result in higher flow velocities and a more uniform horizontal velocity distribution.

The test results demonstrate that a relatively steady flow velocity throughout the test can be achieved. The excess pore pressure within the seabed showed an immediate increase upon the flow release, which is considered to reduce the seabed strength and thereby enhance its erodibility. The measured average erosion depth in normal gravity and centrifuge tests are 2.7mm and 9.8cm (in prototype), respectively.

Future work will focus on scaling up the device and integrating advanced monitoring technologies to further enhance its capabilities.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support from the Natural Science Foundation of Zhejiang Province (Grant No. LR23E090001) and the National Natural Science Foundation of China (Grant Nos. 52571309).

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