SPH modelling of submarine debris flow and turbidity currents transition and FSI processes

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I. INTRODUCTION

Debris flows are crucial in geological engineering, particularly in modelling submarine landslides and the impact of gravity flows on underwater structures. Several models have been developed to simulate debris flows and their associated fluid-structure interaction (FSI) problems. However, most existing models fail to account for the transition of debris flows to turbidity currents. This transition involves the transformation from a non-Newtonian fluid to a Newtonian flow, and neglecting it can lead to underestimation of the forces acting on solid structures. Although turbidity currents have a lower density than debris flows, their velocity and interaction area are significantly larger. In fact, turbidity currents can cause more severe damage to underwater structures than debris flows themselves, and this aspect should not be overlooked.

In this study, we present a numerical model for simulating the transition between debris flows and turbidity currents using the weakly compressible Smoothed Particle Hydrodynamics (SPH) method. The key feature of our model is the incorporation of the debris flow to turbidity current transition process, achieved through a particle splitting technique. The splitting criterion is based on evaluating the effective shear stress acting on a debris fluid particle, which aligns with one of the most widely accepted mechanisms for flow transition. Moreover, to enhance numerical accuracy at the interface between different materials, we introduce a new interface treatment method in this study.

II. MATERIAL AND METHODS

A. Governing equations

The governing equations of the model originated from conservation laws can be written as follow

$$\frac{\mathrm{D}\rho_\alpha}{\mathrm{D}t} = -\rho_\alpha \nabla \cdot \boldsymbol{v}_\alpha \tag{1}$$

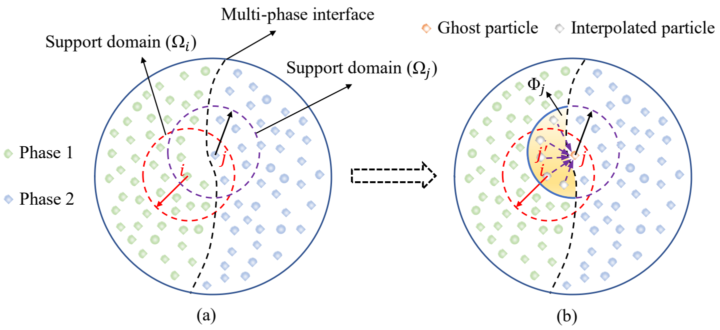
$$\frac{\mathrm{D}\boldsymbol{v}_\alpha}{\mathrm{D}t} = \frac{1}{\rho_\alpha} \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} \tag{2}$$

where the subscript α denotes material properties, ρ is density and t is time, $\boldsymbol{v}$, $\boldsymbol{\sigma}$, and $\boldsymbol{F}$ denote velocity vector, stress tensor and external force, respectively.

B. Multi-material interface treatment

The δ-SPH [1] model is employed to discretize the governing equations. However, the standard density diffusive term can only be applied within the same material, which limits stability at multi-material interfaces. To address this issue, we propose a modification of the density calculation based on the use of ghost particles (see Fig. 1). The modified density calculation is as follows

$$\rho_j^* = \frac{\sum_{j' \in \Phi_i} \rho_{j'} W_{jj'} m_{j'}/\rho_{j'}}{\sum_{j' \in \Phi_i} W_{jj'} m_{j'}/\rho_{j'}} \tag{3}$$



(a) (b)

Fig. 1 Density correction for multi-material interface

C. Particle splitting model

In this study, we employed the following cubic splitting scheme [2] (see Fig. 2) to describe the transformation process from debris flow to turbidity currents. The properties of the daughter particles are assigned as follows:

$$\begin{cases} \boldsymbol{x}_\kappa^{\text{daughter}} = \boldsymbol{x}_\kappa^{\text{mother}} \pm \sqrt[3]{V_{\text{mother}}}/4 \\ m^{\text{daughter}} = m^{\text{mother}}/8;\ h^{\text{daughter}} = h^{\text{mother}}/2 \\ \boldsymbol{v}^{\text{daughter}} = \boldsymbol{v}^{\text{mother}};\ \boldsymbol{a}^{\text{daughter}} = \boldsymbol{a}^{\text{mother}} \end{cases} \tag{4}$$

where $\boldsymbol{x}_\kappa$ represents the spatial coordinates

During large-scale transitions, the splitting process can be highly time-consuming. To address this issue, we propose a GPU-accelerated parallel splitting model. This model enables the concurrent execution of multiple particle splitting processes, as illustrated in Fig. 3. Before the simulation begins, we pre-extend the computational space beyond the initial computational domain to accommodate all the split particles (see Fig. 3(a)). The split particles are then inserted into the computational space in an orderly manner (Fig. 3(b)) and labelled according to the mapping relationship shown in Fig. 3(c). This ensures that the particle information is efficiently assigned using Eq. (4).

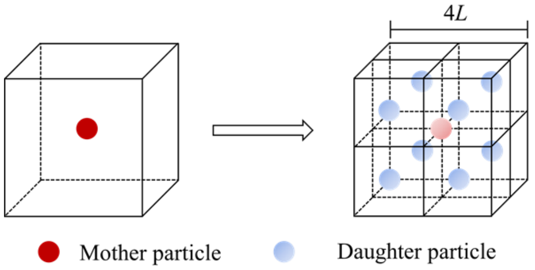


Fig. 2 Particle splitting process in three-dimension

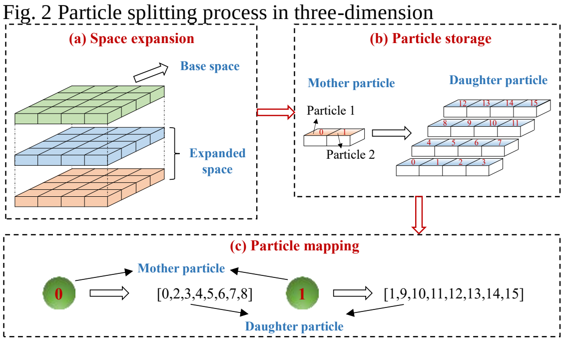


Fig. 3 Particle splitting based on parallel strategy

III. NUMERICAL INVESTIGATIONS

In this section, we conduct investigations of two benchmark problems: the submarine landslide-induced wave process and the impact of submarine landslides on pipelines.

A. *Submarine landslides induce waves*

In this subsection, we validate the proposed debris flow-turbidity currents transformation model by simulating a submarine landslide process. The model's geometry is shown in Fig. 4, with a width of 0.15 m.

We first present the simulation results of the submarine landslide at typical moments and compare them with experimental results [3]. Additionally, we compare our results with those obtained using the standard δ-SPH model and the SPH mixture model [4] (see Fig. 5). The results of our proposed model show that turbidity currents begin to form at the head of the debris flow under fluid shear stress and increase with the sliding velocity of the soil. In the final stage, massive turbidity currents are suspended above the debris flow. The entire landslide process is consistent with experimental observations.

Although the standard δ-SPH model and the SPH mixture model can effectively characterize the movement of the debris flow, they fail to capture the phenomenon of debris flow-turbidity currents transformation accurately. To further validate our model, we quantitatively compare the soil sliding distance at each stage (see Fig. 6). Before the moment of T7, the simulation results of our model closely match the experimental results and are consistent with results from other studies. After the moment of T7, the results of our model deviate slightly from the experimental data.

Additionally, we compare the maximum suspended height of the soil in the water at the final moment, as shown in Table 1. The maximum suspended height obtained from our study matches the experimental data, indicating that the proposed SPH model can effectively capture the transformation phenomenon.

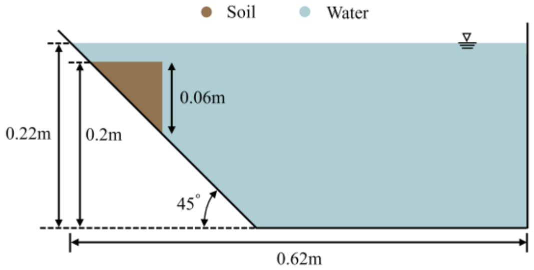


Fig. 4 Geometry of the submarine landslide model

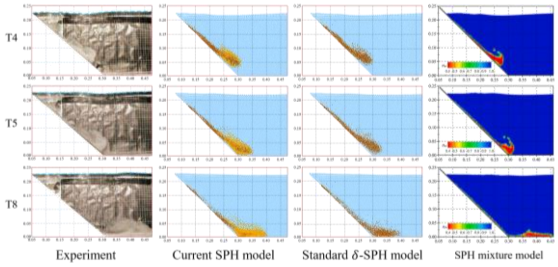


Fig. 5 The results of submarine landslide process at each moment, where $T = t/(0.2/g)^{0.5}$

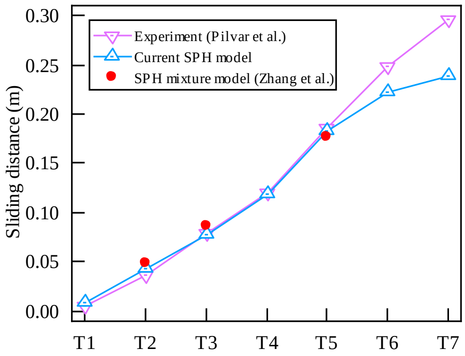


Fig. 6 Variation of soil sliding distance with time

Table 1 Comparison of soil heights at the final moment

	Height (m)	Error (%)
Experiment	0.07	0
Current SPH model	0.061	12.857
SPH mixture model	0.0275	60.714

B. *Submarine landslide impacts a pipeline*

The reference for this section is the submarine debris flow impact pipeline experiment conducted by Zakeri et al [5]. The schematic of the experimental setup is shown in Fig. 7, where D represents the pipeline's diameter.

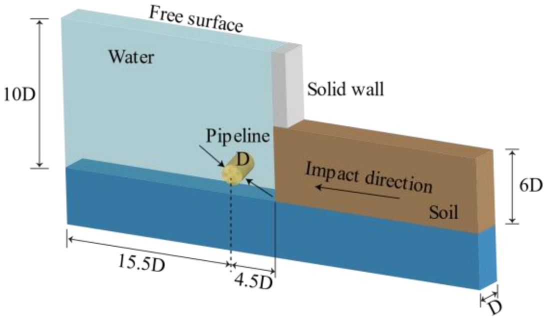


Fig. 7 Initial configuration of the submarine landslide impact pipeline

We first present the schematic results of the impact process at three key moments (see Fig. 8). In the first moment, the front end of the debris flow makes initial contact with the pipeline and splits into two parts, each continuing along the surface of the pipeline. Simultaneously, a slight hydroplaning phenomenon occurs in the lower soil layer. In the second moment, significant turbidity currents are generated around the pipeline (marked by the red dashed line in Fig. 8), and this phenomenon is effectively captured by our proposed model. In contrast, both the grid method and the standard δ-SPH method fail to capture this process accurately. In the final moment, the experiment shows substantial turbidity currents enclosing the pipeline, with a clear hydroplaning phenomenon occurring in the soil.

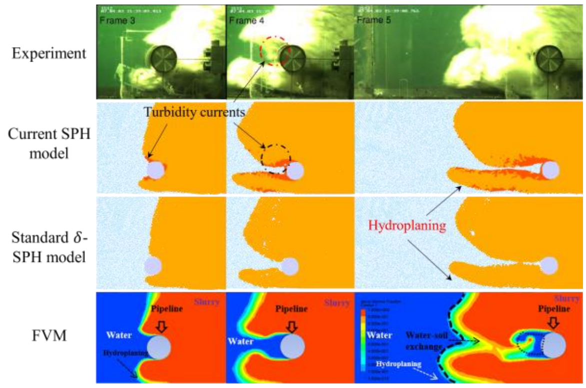


Fig. 8 Different stages of submarine landslides impacting pipeline

Subsequently, we quantitatively analyse the drag force exerted on the pipeline for different clay contents. Figure 9 illustrates the temporal variation of the drag force under three different clay contents. The results demonstrate that if the transition phenomenon between debris flow and turbidity current is not considered, the amplitude of the drag force obtained is significantly smaller compared to other numerical results. These findings highlight the accuracy and effectiveness of the proposed model in simulating impact problems.

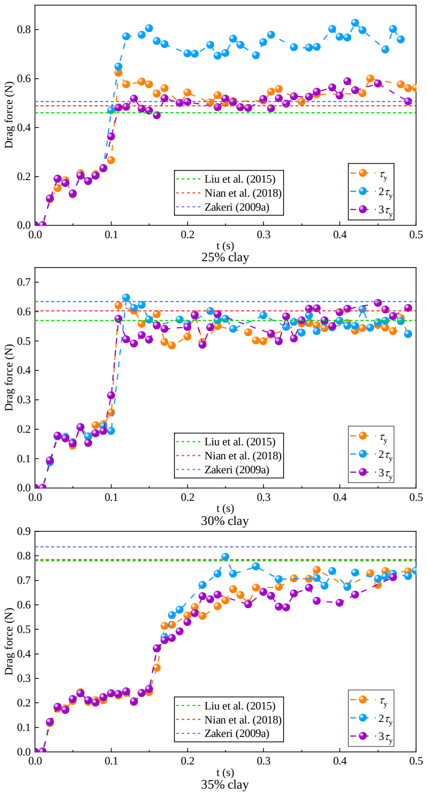


Fig. 9 Variation of drag force on the pipe over time

IV. CONCLUDING REMARKS

In this study, we propose a novel interface treatment method and a parallel particle splitting model to simulate the debris flow-turbidity currents transition and the corresponding FSI processes. Through various case tests, the proposed SPH model demonstrates both accuracy and stability.

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