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Mitigating Geohazards: CFD-Driven Analysis of Viscoplastic Debris Flow Impact on Resilient Oil and Gas Pipeline Design in Alpine Terrains

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ABSTRACT

Debris flow is one of the catastrophic geohazard, poses significant threat to all system of infrastructure including buildings, bridges, pipelines and retaining walls. For the sustainable design of oil and gas pipeline prone to debris flow hazard, it is crucial to consider the expected debris flow impact forces to ensure the safe and effective performance of pipeline. This study numerically investigates the dynamic impact of viscous debris flow on exposed pipeline. Altair Hyperwork CFD software was utilized to perform numerical investigation in CFD environment, simulating two-phase debris flow. Hershel Bulkley rheology and Spalart-Allmaras turbulence model was adopted to simulate the complex interaction of debris flow on pipeline. The results revealed that debris flow dynamics are highly dependent on sediment composition, fine content, and flow volume. These factors significantly influence the flow behavior and its potential impact on pipeline infrastructure. Furthermore, this study highlights the critical role of impact forces due to debris flow in pipeline design to enhance the safe and longevity of pipeline system in alpine terrain. The findings underscore the need for comprehensive approach of pipeline design that integrate the advanced numerical techniques with thorough understanding of local geological conditions.

1. Introduction

Debris flow is a catastrophic geohazard characterized by the rapid movement, large volume, and wide range of poorly sorted sediments [1]. It occurs from extremely turbulent (dilute) to highly viscous (muddy) form due to sediment concentration, fine content, and types of fluids [2].The rapid mass movement of water-saturated debris exert tremendous forces on structures in its path, making it a critical concern for the highly evolving oil and gas industry in alpine terrain [3]. The oil and gas

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sector's increasing expansion into challenging terrains, coupled with the potential impacts of climate change on the frequency and intensity of debris flows, necessitates a re-evaluation of pipeline safety standards. Recent failures of pipelines in Canada, China, Europe, and the North America [4–7] have sent shockwaves through the pipeline industry, emphasizing the urgent need to enhance existing design and protection strategies. These incidents have highlighted the limitations of current approaches and underscored the importance of incorporating advanced modelling techniques to comprehensively analysed the risk associated with pipeline design and maintenance.

In most recent time, debris flows impact have been analysed by experimental and numerical investigations. Small-scale experimental modelling provides the essential opportunity to examine debris flows under controlled conditions [8,9] and provide crucial physical insights into complex processes with detailed knowledge of initial and boundary conditions [10,11]**.** Flume experiments became popular in studying the impact forces of debris flows at different obstacles such as resistant barrier, bridge pier, dams [8,12,13] in last two decades. However, this approach has difficulty of scaling all physical variable and demands considerable investment, and often only a few experimental realizations have been conducted in the literature. On the other hand, numerical models are a legitimate and potential substitute for physical models. Scale effects do not have a direct impact on them, and therefore necessitate fewer economic resources. Additionally, these simulations are reproducible without any constraints related to the availability of materials. Debris flow can either be modelled as continuum [14–16] or discrete material [17,18] based on the type of material involved in debris flow. Continuum-based numerical approaches are available, both in 2D depth-averaged (DA) [14,19,20] and three-dimensional (3D) form [21,22]. Most of the continuum-based model solved the Navier-Stokes equations which describe the continuity and momentum conservation equation. The dynamic impact pressure observed form the 3D impact modelling help to enhance the understanding of debris flow impact on pipeline section crossing the uneven mountainous terrain.

Therefore, this study aims to contribute in the critical field of viscoplastic debris flow impact on exposed pipelines by utilizing advanced Computational Fluid Dynamics (CFD) simulations. CFD model have developed in Altair Hyperwork CFD software by incorporating complex rheological and turbulence models. we seek to provide valuable insights into the behaviour of debris flows and their interaction with pipeline structures. Our research not only addresses the immediate concerns of the pipeline industry but also paves the way for more resilient and sustainable infrastructure design in mountainous regions globally.

2. Methodology

2.1 Creation of CFD Domain

The 3D computational fluid dynamic (CFD) environment were utilized to simulate the impact mechanism of viscous debris flow on 2” (52 mm) pipe model. The debris flow propagation and impact were observed in 9 m long and 0.25 m wide wave flume. The dimension and boundary conditions were strictly followed by the experimental setup of Khan *et al.*, (2024) [3]. The typical geometry and boundary condition of CFD model have been shown in Figure 1.

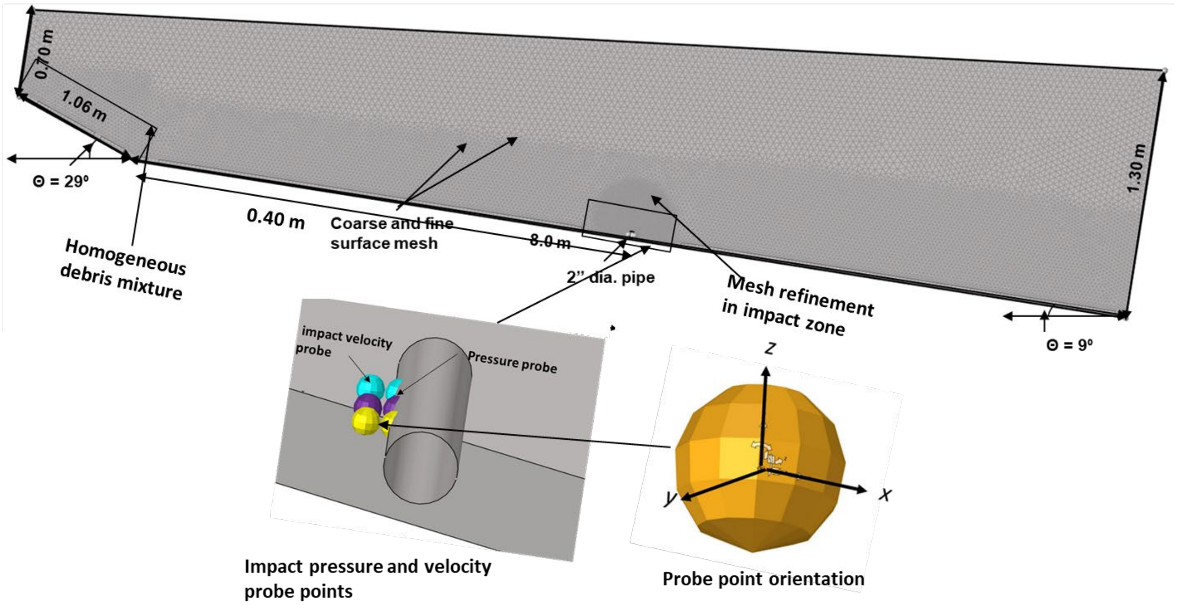


Fig. 1. CFD domain of debris flow propagation and impact mechanism

The height of the wave flume varied form 0.70 m to 1.30 m to facilitate the prorogation and impact mechanism in experimental and numerical modelling. The flume channel's left side edge, bed surface, and right-side edge were represented as walls, replicating the laboratory condition. A no-slip boundary condition with equivalent sand grain roughness, r_s of 0.002 mm [23] was applied to these wall surfaces, to avoid debris flows from slipping or sliding along the surfaces. The top and rear walls of the domain was modelled as free-slip wall boundary conditions (outlet) in which air was allowed to freely move in or out. This assumption had reduced the computational time required for the air flow field on those surfaces, without affecting the debris flow in the channel.

2.2 Mesh Size and Probe Point Locations

Several mesh and time step convergence trial were performed to obtain the suitable mesh and time step size for transient debris flow simulation whose detail can be found on our recently published article [3] . A global meshing size of 0.05 m with time step 0.001s were chosen and applied throughout to discretize the volume domain of the CFD model as depicted by Figure 1. Furthermore, a finer meshing size of 0.03 m was employed along the debris flow path to observe the flow front characteristics of debris flow. Additionally, a boundary layer was created using fraction of surface mesh techniques at the bed and around the pipe model to accurately capture the debris flow interaction around these surfaces. Overall, 432068 nodes were created to generate the 86467 2D triangular surface and 2093391 3D quad elements in the CFD model. The decision to use quad elements from the Hyper work meshing library was based on their random orientation and suitability for transient turbulent flows.

In the CFD model, debris flow front velocity, v and impact pressure, p were computed and observed in the post processing stage by defining three probe points along the cross-section of the channel. The size of the probe points was 0.02 m diameter and were positioned at 3.95 m, and 4.0 m across the pipe surface, as shown in Figure 1. The probe points located at 3.95 m was used to record the time history of velocity in the *x-, y-* and *z-* directions, while the probe points on the pipe surface recorded the pressure time history in each simulation. The average debris flow front velocity and impact pressure were later computed accordingly.

2.3 Debris Flow Simulation

Viscoplastic debris flow samples were prepared in the laboratory by mixing gravel, sand, clay and water at required proportion. The debris flow was defined in 3D continuum domain by density, Spalart Allmaras turbulent and Hershel-Bulkily rheological model in transient flow condition. The Typical detail of debris flow samples is presented in Table 1.

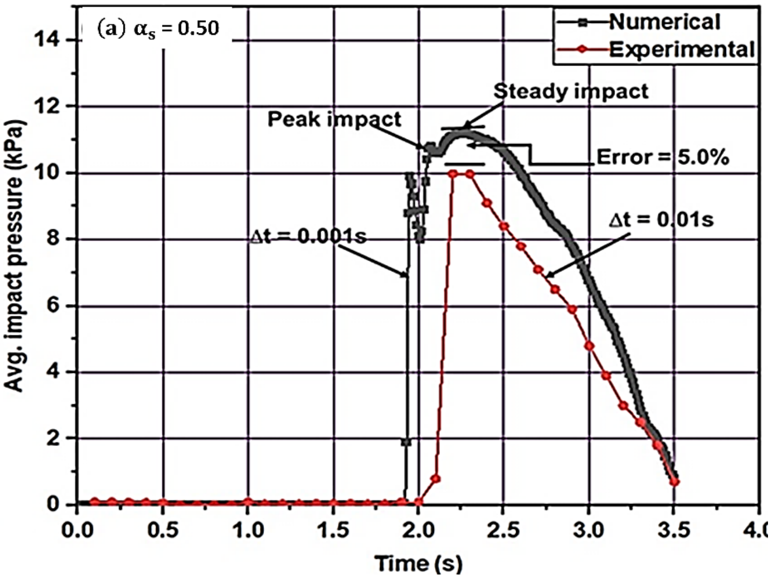
Table 1
Composition and characteristics of debris flow samples used in CFD simulation

No.	Solid volume fraction (α_s)	Percentage by mass (%)			Bulk density (ρ) (kg/m^3)	H-B rheological model $\tau = \tau_y + k\dot{\gamma}^n$	Remark
		Water	Gravel and sand	Clay			
1	0.50	40	52	10	1720	$\tau = 66.9 + 25.7\dot{\gamma}^{0.20}$	Medium viscous
2	0.55	34	54	12	1810	$\tau = 85 + 40\dot{\gamma}^{0.17}$	Highly viscous
3	0.60	28	60	12	1900	$\tau = 101 + 35\dot{\gamma}^{0.16}$	Highly viscous

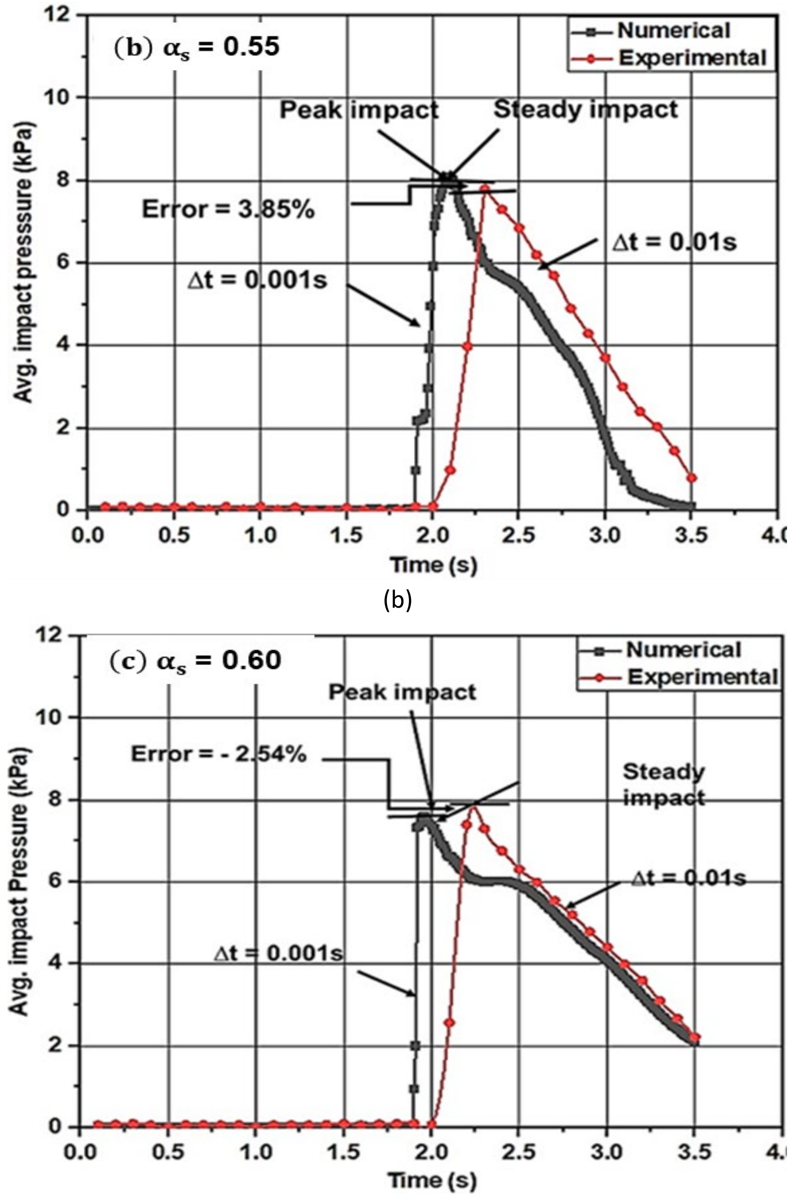
The total weight of the sample was 120 Kg in each case however, the bulk density of the fluid varied from 1720-1900 Kg/m^3 depending on the solid volume fraction. The rheological investigation of samples was performed using digital hybrid rheometer (DHR-1) with vane rotor on fluid phase whose detail can be found on our previous published article [24].

3. Result

The impact velocity and pressure time histories of debris flow in each case was recorded by probe points defined in pre-processing stage. The numerical simulation was validated with the results observed in experimental investigation as presented by Figure 2.



(a)



(b)

(c)

Fig. 2. Average impact pressure various at different solid volume fraction α_s (a) 0.50) (b) 0.55) (c) 0.60

It had been noticed that the impact pressure observed in CFD simulation was slightly higher at medium viscous case in the experimental modelling. This disparity may be attributed to the various assumptions made in the CFD modelling to replicate the complex experimental debris flow scenarios. According to Cui *et al.*, (2015) [25], the peak and steady impact pressures are significant in designing the structures against debris flow hazards. Therefore, In the current CFD modelling, peak and steady impacts were distinctly observed in medium viscous debris flows i.e., α_s = 0.50, as depicted in Figure (2a). Further in case of highly viscous debris flow CFD impact pressure was significantly comparable with experimental pressure distribution, which support the 3D continuum assumption of debris flow in viscoplastic regime.

Moreover, velocity distribution contour of debris flow along the channel was plotted in each simulation which has been presented in Figure 3. It can be observed from Figure 3 that the debris flow rushes down the channel and impact the pipe at different time at fixed gradient (*i.e,* 9 degree*)* due to the increase in viscosity with increasing solid volume fractions.

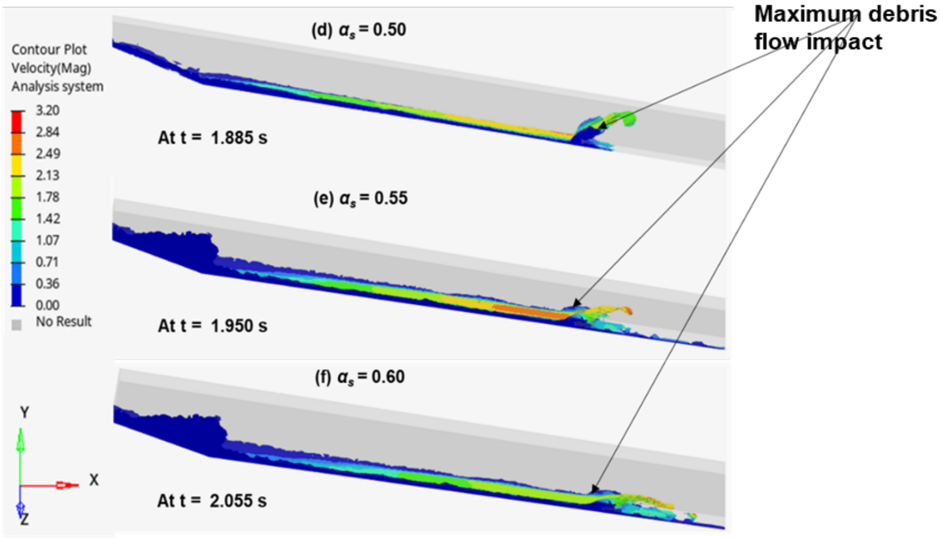


Fig. 3. Velocity contour and maximum debris flow impact from medium to high viscous debris flow

Furthermore, the release volume of the debris flow was sufficient to exhibit both peak and steady impacts for medium viscous cases. These hydrodynamic forces are the primary factors that significantly influence the performance of the pipeline in alpine terrain The CFD simulation also revealed that the impact velocity varies significantly with changes in solid volume fractions resulting increase in viscosity and density. Therefore, pipeline engineer must have the sound understanding of the Alpine terrain and type of debris flow expected to occur in the design life of pipeline.

Moreover, dynamic characteristics of debris flows observed in CFD simulation have been summarized in Table 2. It has been found that the maximum impact velocity and pressure (p_{peak}) was observed in medium viscous case at (α_s) = 0.50, i.e., 2.78m/s and 11.34 kPa respectively.

Table 2
Dynamic characteristics of viscoplastic debris flow observed in CFD simulation

No.	Solid volume fraction (α_s)	Bulk density (ρ) (kg/m^3)	CFD observed dynamic parameter			Remark
			v (m/s)	p_{peak} (kPa)	p_{std} (kPa)	
1	0.50	1720	2.78	11.34	11.30	Medium viscous
2	0.55	1810	2.2	8.15	8.10	High viscous
3	0.60	1900	2.0	7.66	7.60	High viscous

In summary, studying debris flow impact on exposed pipelines is crucial for understanding the structural behavior, failure mechanisms, and erosion effects. Therefore, to withstand the catastrophic failure pipeline must be design by considering the viscoplastic debris flow impact pressure in Alpines terrain.

4. Conclusions

The investigation of viscoplastic debris flow impact on oil and gas pipelines in alpine terrain reveals critical implications for resilient infrastructure design. In this study, dynamic response of viscoplastic debris flows varied by solid volume fraction were investigated by CFD driven analyses. CFD simulation were performed by Altair Hyperwork CFD with Acusolve (a finite element solver).

Dynamic characteristic such as maximum velocity and impact pressure were observed in three different viscous flows at 52 mm diameter pipe model. Our study demonstrates that the complex rheological behaviour of debris flows, characterized by their viscoplastic nature, significantly influences the magnitude and distribution of forces exerted on pipeline structures. It was found that solid volume fraction significantly influenced the flow regime, hence the impact mechanism on the exposed pipeline. Maximum impact pressure was observed in case of solid volume fraction (α_s) of 0.50 i.e., 11.34 kPa. The study shows that debris flow characteristics are heavily influenced by volume, geology, and material composition. This underscores the need for site-specific risk assessments and tailored design solutions, moving beyond one-size-fits-all approaches in pipeline engineering.

In conclusion, the integration of viscoplastic debris flow impact analysis into the design process is not merely an additional safety factor but a fundamental requirement for ensuring the longevity, reliability, and sustainability of oil and gas pipelines in alpine terrain. This approach represents a paradigm shift in pipeline engineering, moving from reactive to proactive design strategies in the face of complex geohazards. Future research should focus on refining predictive models, developing innovative protective measures, and establishing comprehensive design guidelines that explicitly account for the unique challenges posed by viscoplastic debris flows in mountainous regions. Furthermore, risk management methodologies mostly rely on the vulnerability of pipeline which directly links to impact mechanism of debris flows on pipeline. Therefore, more experimental and numerical investigations are needed with wide range of debris flows that typically occur in natural settings to mitigate the geohazard effect on the oil and gas pipeline.

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