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Fluid-particle dynamics in submarine landslide impacts on sea cables: a numerical study

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ABSTRACT: This study presents a numerical model that couples the Discrete Element Method (DEM) with the Lattice Boltzmann Method (LBM) to investigate the influence of pore pressure on submarine landslides impinging against cables. DEM is employed to simulate the mechanical behaviour of granular materials, while LBM models the fluid dynamics of pore water. This coupled approach enables a detailed analysis of the interactions between submarine landslides and submarine cables, capturing the dynamics of pore pressure and its effect on the velocity field of both grains and fluid. The model has been benchmarked against values from the literature, demonstrating its reliability and accuracy in reproducing observed phenomena. Results highlight the critical role of pore pressure on the velocity field and forces acting on intruders.

Keywords: Submarine landslides; Subsea cables; Numerical modelling; Discrete Element Method; Lattice Boltzmann method

1 INTRODUCTION

The offshore wind farm industry has been growing steadily in recent years (Díaz & Guedes Soares, 2020). Offshore wind farms consist of groups of wind turbines located offshore. The energy produced by these wind farms must be transported to onshore structures for use and distribution. To accomplish this, sea cables are employed as part of the transportation network. These cables play a crucial economic and strategic role in global energy supply chains (Guo et al., 2024).

While cables can be buried for protection, this approach is often expensive and challenging due to geological factors or technological limitations (Dutta & Hawlader, 2019). As a result, despite their importance, cables are frequently laid directly on the seabed or with minimal burial depth. This method, although more economical, exposes the cables to external events, such as submarine landslides and other geological phenomena. Since cables are often located in areas prone to submarine landslides, they risk being snapped, deformed, or broken by these events (Gao, 2017). Their failure can lead to energy disruptions and other significant issues. Therefore, it is essential to understand the conditions under which cables may fail.

This topic has been explored in recent literature, with various models proposed to estimate the forces acting on cables. Research in this area includes numerical studies using continuum models (Guo et al., 2022; Zhang et al., 2019).

Despite the material available in the literature, most studies utilize continuum numerical models. While these models effectively replicate submarine landslides composed of fine-grained materials, they become less suitable for landslides composed of debris, especially if the size of the debris is comparable to the size of the cable. In such cases, discrete models provide a more appropriate framework for studying the forces exerted by a landslide on an object (Leonardi, 2015). Moreover, coupling discrete models with continuum models allows for the simultaneous analysis of solid and fluid components of the forces acting on the cable. This continuum-discrete approach also allows studying the influence of pore pressures—a factor often overlooked in previous studies (Polanía et al., 2024)—on both the forces acting on the cable and the motion of individual particles within the landslide.

This study investigates a landslide composed of coarse material saturated with water. The system is modelled using an in-house coupled numerical approach that integrates DEM with LBM. Originally developed by Leonardi, (2015), DEM captures the granular behaviour of the landslide, while LBM simulates the fluid environment, including pore pressures within the grains. By coupling DEM and LBM, this approach

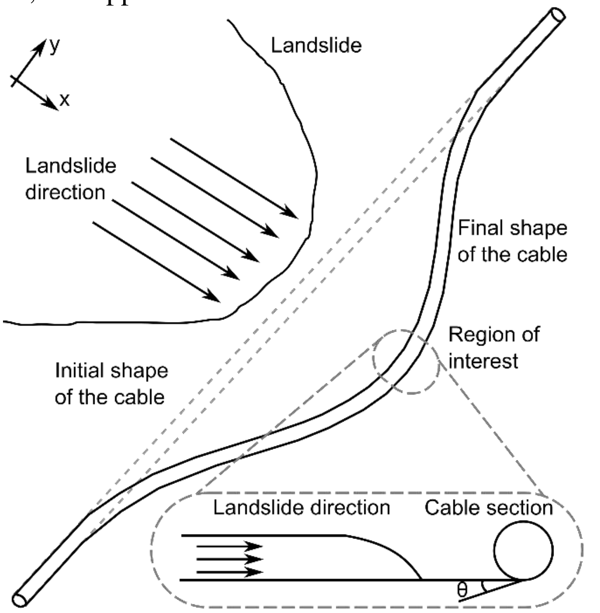

Figure 1. Schematic of the studied problem: a submarine landslide on a slope with incline θ impacts a cable, causing its displacement. The analysis focuses on the cable cross-section, where the cable maximum displacement occurs.

offers a robust framework for analysing interactions between landslide and cable.

Figure 1 illustrates the studied problem, focusing on the central section of the cable. To investigate the complex interactions between a submarine landslide and a subsea cable, this study examines the behaviour of an intruder moving through a granular medium. This setup approximates a landslide mass advancing at a constant velocity, representative of real-world conditions. Specifically, once a landslide is triggered and impacts the cable, the cable moves with the landslide until reaching its maximum extension. At this point, the cable becomes stationary, while the landslide continues to exert forces on it at an approximately constant velocity.

The DEM-LBM model is employed to analyse the forces acting on the cable under these conditions, with a particular focus on the role of pore pressure in the system. This assumption provides a controlled setup to validate the DEM model, serving as a necessary preliminary step to assess its accuracy and reliability. This approach enables a detailed investigation of the dynamic interactions between landslide kinematics and the cable, capturing the contributions of both solid and fluid phases to the impact forces, as well as the mobility and resistance of the surrounding soil.

2 METHODS

2.1 Discrete phase

DEM models the grains of a landslide as clusters of elements (Teufelsbauer et al., 2011) with varying shapes, such as spheres or cylinders. Each element is represented as a Lagrangian point, characterised by its mass and rotation. The evolution of these parameters is governed by Newton's equations of motion.

In this study, the elements are assumed to 2D and circular. The elastic deformation is tracked by allowing the elements to overlap, with a repulsive force calculated from the overlap itself (Leonardi et al., 2016). The normal force is calculated using a linear dashpot model. The resulting force incorporates both elastic and viscous contributions by:

$$F_n = k_n\xi + 2A\sqrt{k_n\widetilde{m}}\xi \qquad (1)$$

where k_n represents the stiffness of the elastic contribution, ξ is the overlap, A is the damping factor, and $\widetilde{m}$ is the effective mass. The tangential force is assumed to be proportional to the component of relative velocity of two elements in contact.

2.2 Continuum phase

The continuum phase is modelled using LBM, a solver for the Boltzmann equation. This method has proven to be solid and reliable for solving complex fluid mechanics problems (Mohamad, 2011). LBM efficiently models the fluid behaviour by simplifying the vast number of molecules into groups that behave similarly, rather than tracking each molecule individually. This collective approach uses a distribution function $f(\boldsymbol{x}, t, \boldsymbol{c})$, which represents the probability of finding a fluid particle at a position $\boldsymbol{x}$ and at time t with a velocity $\boldsymbol{c}$. By discretizing the velocity space into a limited set of possible velocities c_i, LBM reduces the problem degrees of freedom, making the solver more efficient. Macroscopic hydrodynamic quantities are then obtained by summing these distribution functions, relying on the principles of mass and momentum conservation (Mohamad, 2011).

2.3 Continuum-discrete coupling

In this study, the DEM and LBM are coupled. The motion of the fluid influences the motion of the particles, and vice versa (Leonardi et al., 2014).

The Immersed Boundary Method (IBM) coupling scheme is applied at the particle-fluid interface. IBM is implemented via direct forcing to integrate the DEM and LBM for simulating particle-fluid interactions (Leonardi et al., 2014). In this framework, the fluid forces acting on an element are calculated based on the relative velocity between the element and the surrounding fluid, ensuring momentum exchange between the particles and the fluid. The direct forcing method may be well-suited for simulations involving dense submarine landslides, where particle movement influences fluid dynamics. For each lattine node immersed within a particle or within the intruder, the hydrodynamic force is computed as follows:

$$F_{\mathrm{w,node}}(x,t) = \rho_{\mathrm{w}}(x,t)[u_{\mathrm{w}}(x,t) - u_{\mathrm{c}}(x,t)] \quad (2)$$

Where F represents the force, the subscript w and c represent the water and cylinder (and discrete element) velocity and ρ_{w} is the density of water. The resultant force on a cylinder (or intruder) is given by the summation of Eq. 2:

$$F_{\mathrm{w}} = \sum F_{\mathrm{w,node}} \quad (3)$$

The resultant force acting on an element (or an intruder) is the summation of Eqs. 1 and 3, corresponding to the fluid and discrete componets, respectivelly.

3 NUMERICAL ANALYSES

Two sets of numerical analyses are conducted. First, the DEM model is validated against the results from Seguin et al., (2016). Then, the coupled DEM-LBM model is applied to explore a more complex scenario. For clarity, the DEM analyses are referred to as "Dry," while the DEM-LBM analyses are referred to as "Immersed." The numerical parameters used in the analysis are presented in **Erreur ! Source du renvoi introuvable.**. This choice was made because the time step and lattice discretization provided a resolution suitable for detailed observations. The other parameters correspond to the material properties reported in Seguin et al. (2016).

3.1 Granular flow against an intruder

Seguin et al. (2016) employed a series of experiments for examining the interactions between an intruder and a granular medium composed of smaller cylindrical particles (see Figure 2). The experimental setup involved moving a large cylinder (intruder) at a constant velocity through a two-dimensional assembly of approximately 8,000 particles, with diameters ranging from 4 to 5 mm and a height of 3.2 mm. The intruder diameter, D_i was four times larger than that of the particles. All elements were confined between two horizontal glass plates with a slight gap, allowing for unrestricted horizontal motion. They were arranged in

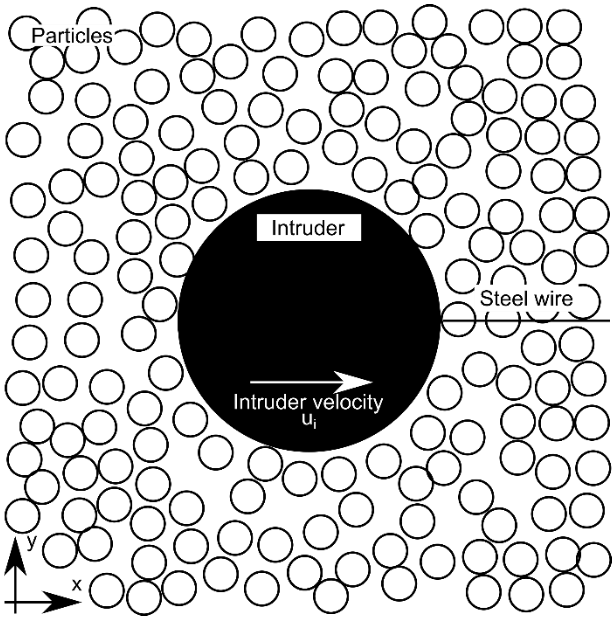

Figure 2. Schematic of the experimental setup presented by Seguin et al. (2016). The intruder moves through a granular packing in a two-dimensional configuration.

a dense packing with an initial packing fraction of approximately 0.76–0.80. The intruder was pulled horizontally using a steel wire connected to a linear stepper motor, with its velocity u_{i} varying between 10^{-4} and 3 mm/s. This configuration is analogous to the field-scale flow-cable interaction described in Figure 1, where the motion of the intruder represents the landslide-driven displacement of the cable before it becomes stationary. The DEM model was initialized by allowing the particles with low friction to settle under gravity, replicating the initial configuration of Seguin et al., (2016). Once equilibrium was reached, friction was restored. Then, gravity was applied in the same direction as in the experiments (negative y-direction in Figure 2) to ensure consistency.

Seguin et al. (2016) recorded the forces acting on the intruder in the velocity range reported above. The force history shows oscillations due to micro-interactions between intruder and particles. Figure 3 shows our numerical results for the force history, which replicate this behavior, highlighting the oscillations caused by the interactions between the intruder and the surrounding particles. The force increases during the compression phase, followed by a

Table 1. Numerical parameters

Material constant	Symbol	Value
Time step	Δt	$5 \cdot 10^{-5}$ s
Fluid cell	Δx	$0.8 \cdot 10^{-3}$ mm
Fluid density	ρ_{w}	1000 kg/m^3
Cylinder density	ρ_{c}	1280 kg/m^3
Linear stiffness	k_{n}	1000 N/m
Restitution factor	e	0.88

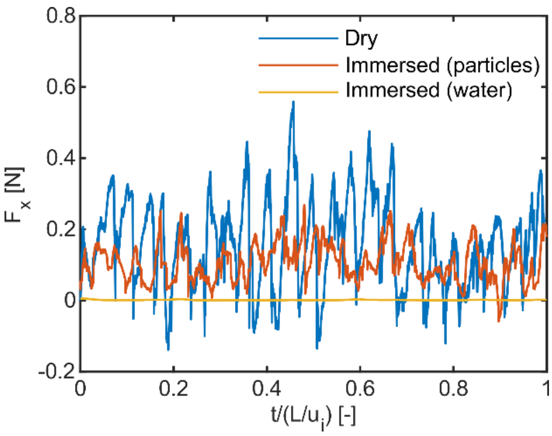

Figure 3. Force history in dry and immersed (particle and water contribution) simulations with an intruder moving at 1.00 mm/s.

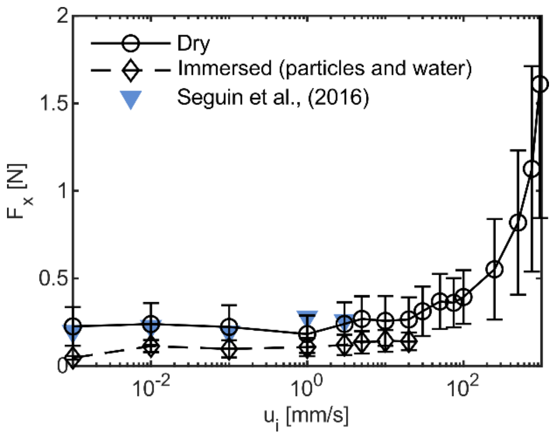

Figure 4. Comparison between numerical results (dry and immersed) and data from Seguin et al., (2016).

decrease as the intruder is pulled. This cyclic pattern of force increase and decrease repeats, with minor variations, as the intruder moves through the domain of particles, resulting in similar force patterns throughout the simulation. The mean value of the force oscillates around 0.19 N, which is close to the value reported by the authors (0.21 N). The time is scaled to the duration required to cover a distance of $L =$ 100 mm and is considered sufficient to visualise the force history. Similar behaviour is observed for all velocities tested by the authors.

Figure 4 shows the results from Seguin et al., (2016) and our dry analyses. These force datasets are used to validate the DEM model. The numerical results match well the experimental results. Although minor differences are present, the numerical model can be considered validated and employed to extend the research presented in the literature. Seguin et al., (2016) studied a problem under quasi-static conditions. Therefore, it is important to determine the velocity of the intruder at which the quasi-static condition is no longer met. Figure 4 also shows the mean force acting on the intruder as a function of its velocity. The mean force remains relatively constant with increasing the intruder velocity up to 20 mm/s. For velocities greater than this threshold, the mean force begins to increase. This observation is supported by the Cauchy number $\mathrm{Ca} = \rho u_{\mathrm{i}}^2/k_{\mathrm{n}}$, which represents the ratio between the inertial force and the compressibility forces in a flow Kesseler et al., (2018). When Ca ≪ 1, inertial forces are larger than viscous forces. Therefore, the mean force is independent of the intruder velocity for $u_{\mathrm{i}} < 20$ mm/s. For $u_{\mathrm{i}} >$ 20 mm/s, the force on the intruder increases sharply.

3.2 Grains and Fluid Flow Against an Intruder

The immersed analyses differ from the previous section by accounting for the presence of water. Figure 3 presents the force history on the immersed intruder at a velocity of 1 mm/s. Both the contributions from the particles and water are shown to quantify the contribution of each component. The contribution from the particles follows the same trend as observed in the dry analysis. However, the oscillations in the force values (due to compression and release) are damped. This damping may be attributed to changes in pore pressures likely playing a key role in reducing the forces acting on the intruder. Interestingly, fluid forces against the intruder are significantly smaller than the forces arising from the interactions with particles because of the small viscosity.

Figure 4 presents the forces acting on the immersed intruder in the velocity range $10^{-3} < u_{\mathrm{i}} < 10$ mm/s. In this range it was shown that Ca ≪ 1, meaning that hydrostatic forces dominate over inertial forces. The figure summarises the contributions from both particles and water in the same series. It can be observed that the magnitude of the force is lower than that in the dry analysis. This reduction can be attributed to the presence of water. As the intruder moves, it increases the pressure in the fluid, which acts against the particles and reduces their displacement. Consequently, the forces acting on the intruder (see Eq. 1) are smaller. Additionally, the error bars are smaller compared to the dry analysis. Again, this damping effect can be explained by the increased pore pressures, which counteracts the displacements of the elements, likely reducing the oscillations around the average value.

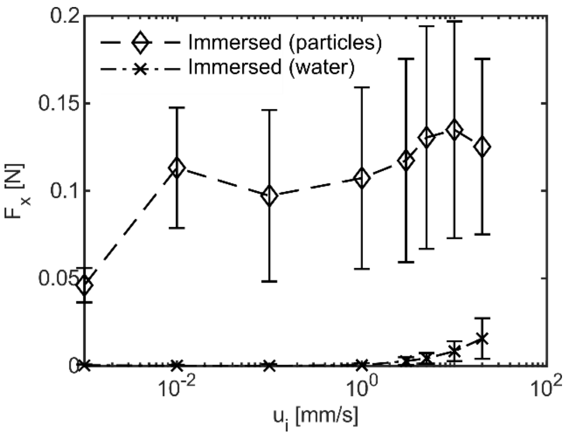

Figure 5. Mean forces acting on the intruder in the immersed simulations as a function of the intruder velocity.

It is important to quantify the force components coming from direct interactions betweenn particles and intruder and from the interactions between water and intruder. This aspect is important to determine which force component of the grain-fluid medium is more important during the impact process Figure 5 shows the force components of the particles and water to the resultant forces acting on the intruder. Like in Figure 4, the analysed interval of intruder velocity is $1 \cdot 10^{-3} < u_\mathrm{i} < 1 \cdot 10^{1}$, mm/s meeting the condition $\mathrm{Ca} \ll 1$. The results confirms what was observed in Figure 3 and 4. In particular, the component from the particles is much larger than the component from the water. The flucturations for the forces due to particles are much larger than those from water, indicating that this force component exhibits greater oscillations around the mean value. It is important to understand that the total force on the intruder is the sum of both particles and water components. A highlight from this analysis is that being able to analyse the two components separately provides a better understanding of the role of pore pressures.

Finally, Figure 6 shows the velocity field of the elements for the simulation with $u_\mathrm{i} = 1.0$ mm/s. As discussed, the influence of the fluid, and in particular the pressure, on the intruder velocity is not negligible. Indeed, the figure confirms how the velocity field is significantly reduced in the immersed case.

4 CONCLUSIONS

The growing importance of offshore wind farms highlights the need to ensure the integrity of cables transporting their energy. This work investigates the impact of submarine landslides on sea cables using a 2D system where an intruder moves through granular media.

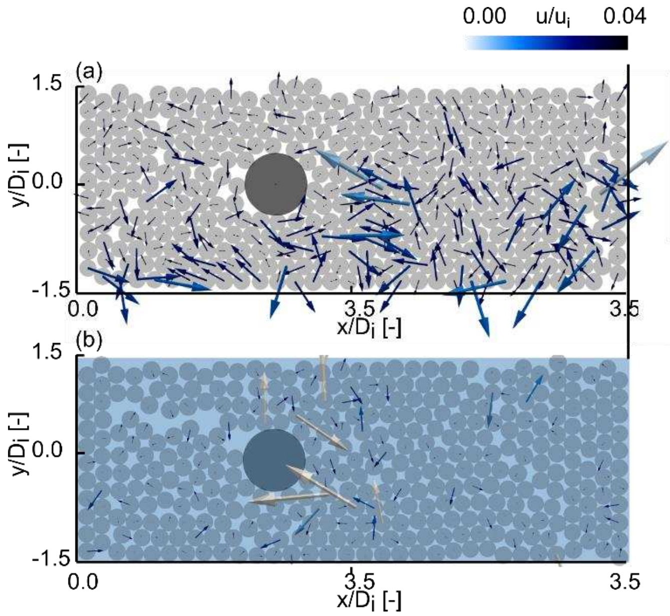

Figure 6. Velocity field of particles around an intruder for (a) the dry simulation and (b) the immersed simulation. The vectors represent particle velocities, with their magnitude indicated by the colour scale where u_i is the intruder velocity. The immersed case highlights the influence of fluid on elements motion compared to the dry scenario.

We propose and validate a novel method to study cable-landslide interaction, focusing on the role of pore pressure in the velocity field and forces on the cable. A section of the cable is modeled as an intruder impacted by a landslide moving at a constant velocity. The method employs a coupled DEM-LBM solver. The approach was benchmarked against Seguin et al. (2016), where an intruder was pulled through dry granular media. The DEM results closely matches the experiments, enabling the extend the method to immersed scenarios with water. This may provides a more realistic representation of submarine environments, with forces on the intruder behaving consistently across both particles and water. However, additional experiments are needed to further validate the model in an immersed scenario and improve the understanding of the studied phenomena. Therfore, planned centrifuge tests will compare numerical results with experimental data, strengthening the method's applicability to studying forces on cables in submarine environments.

AUTHOR CONTRIBUTION STATEMENT

A. Pasqua: Data curation, formal analysis, writing-original draft, software.
A. Leonardi & M. Cabrera: Supervision, writing-reviewing and editing, project administration, funding acquisition.

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