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THE EFFECT OF PARTICLE SIZE, SALINITY, FLOCCULATING AGENTS ON THE PROPAGATION OF MINING-GENERATED TURBIDITY CURRENTS

M. Elerian[1], A.A. Bedón Vásquez[1], D. Enthoven[1], R. Helmons[2], C. van Rhee[1]

Abstract: Renewable energy installations and energy storage solutions require a significant amount of critical raw materials such as nickel, cobalt and rare earth elements. The supply chains of these raw materials face many challenges, e.g., these materials are often found at lower grades on land. These complications motivate the search for new resources. Therefore, the deep sea is looked into as a potential source for such minerals. However, sea bed mining is expected to affect the mined area. One of the concerns is the so-called mining-generated turbidity current, which can cause a negative impact on the deep-sea environment. For that reason, in order to characterize the generated turbidity current, we investigate the generated current experimentally, where cohesive and non-cohesive sediment types are tested using a lock-exchange set-up. Three non-cohesive sediment types are tested in order to investigate the effect of the particle size and initial concentration on the propagation velocity of the current. Moreover, one cohesive sediment, i.e illite, is used to compare the propagation velocity in both saline and fresh water. Finally, we used flocculating agents as a proxy to biological matter, to test its influence on the flocculation process. The results show that using or generating larger particle sizes effectively results in a reduced propagation velocity of the current. In addition, the propagation velocity increases in case of higher initial concentrations. In case of cohesive sediment, natural flocculation (i.e flocculation without using flocculants) occurs faster in saline water than the fresh water. Moreover, using organic flocculants would increase the process of the flocs formation, which results in a lower front velocity and an effectively reduced plume dispersion.

Key words: Deep Sea Mining, Polymetallic Nodules, Turbidity Current, Flocculation.

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1 INTRODUCTION

On the long term, in order to preserve a livable climate on earth, european union aims to reduce greenhouse gas emissions by 80%-95% in 2050 (Scarlat et al.,2015). Employing renewable energy sources and investing in energy storage systems might be the only way to achieve such a goal. However, for instance, to reduce the carbon emissions resulting from the transport sector, electrical cars have to be produced in a continuous pace. Securing the needed metals, e.g., copper, nickel and cobalt, for a constant production rate of such vehicles is a challenge. In fact, many obstacles encounter terrestrial mining for these metals. Notably, the grades of these minerals are reducing on land. Therefore, searching for new possible resources is of high importance to keep supply-chains of these critical minerals active.

At the end of 19th century, polymetallic nodules are discovered at different oceans bed. These nodules consist of different/ high grade minerals such as manganese, iron, cobalt, copper and nickel. Based on that, it is expected that extracting these nodules from the ocean bed will secure the needs for the desired energy transition. Lately, in this regard, Deep Sea Mining (DSM) is introduced as a viable solution to secure these needs. Many scenarios are planned in order to extract the polymetallic nodules; however, they share similar concepts. According to Elerian et al., 2021, mining the nodules consist of three main components: Production Support Vessel (PSV), Vertical Transport System (VTS) and Polymetallic Nodules Mining Tool (PNMT). The PNMT collects the ore from the ocean bed and transports it to the PSV through the VTS. The ore is further processed on the PSV and the remaining water, sediments and waste is sent back to the deep-sea.

Inevitably, within the collection process, the PNMT collects water and sediment together with the ore. Thus, to optimize the transport process of the ore from the PNMT to the PSV, a primary separation process takes place inside the PNMT, where the collected ore is separated from the sediment-water mixture. This mixture is discharged further from the back of the PNMT. The discharged flow from the PNMT passes through 4 regions of interest (Elerian et al., 2021), see Figure 1. Firstly, the discharge region, here the discharge properties (e.g., momentum, buoyancy, volume fluxes) are determined. Secondly, depending on the ratio between momentum and buoyancy fluxes, the discharged flow can be classified to either jet or plume, i.e., for the classification between jets and plumes the reader is referred to Elerian et al., 2021. Thirdly, the impingement region, where the mixture meets the ocean bed. Finally, the turbidity current region, where a turbidity current is formed after the impingement region.

Beyond the impingement region, the generated turbidity current is directed towards all directions as shown in top view in Figure 1. It is challenging to investigate the full-scale generated turbidity current due to the high cost of the field experiment. In order to simplify the investigation process of such complicated current, we hypothesize that the full scale turbidity current consists of many small currents next each other (section A-A in Figure 1). Following this hypothesis, lock-exchange generated current is representative to these small currents in terms of its forward velocities, and thus the transition time between the phases of a propagated current (see Section 3). In this regard, lock-exchange experiments can be a valuable tool to investigate the effect of different parameters on the propagation behavior of the current, e.g. initial concentration, particle size, salinity, flocculants. Therefore, we perform a set of lock-exchange experiments which is about releasing a high density current into a lower density current. However, it is important to note that the lock-exchange generated currents are not scaled to those generated in the mining field due to some limitations such as the free surface in the lock-exchange experiment and a moving discharge source. We believe that the drawn conclusions from these experiments will lead to a better designing approaches of the discharge process.

The discharge process is likely to impact the environment in a negative way. For instance, in case of polymetallic nodules mining operations, it was reported by Sharma, 2015 that the mortality rate of the fauna has increased, not to mention that the alteration of chemo-physio sediment properties resulting from sediment transport would lead to a dramatic loss in the benthic organism's habitat. From this perspective, we believe that optimizing the discharge process to increase the settling flux of the discharged sediment particles could minimize the affected region, and thus lead to reduced environmental impact. In order to achieve this, we present a set of experiments to quantify and understand the formed turbidity currents behind the PNMT (region 4 in Figure 1), where we call it "mining-generated turbidity currents". We assess the effect of particle size of non-cohesive sediment on the current. Moreover, we experiment the cohesive sediment in saline and fresh water to investigate the effect of the flocculation on the propagation velocity of the current. Finally, we assess the effect of the propagation speed of the current in case of using flocculants. Thus, the paper proceeds as follow, first, we start with explaining our experimental methodology, second, the results and discussions are presented, and at the end we draw up our conclusions.

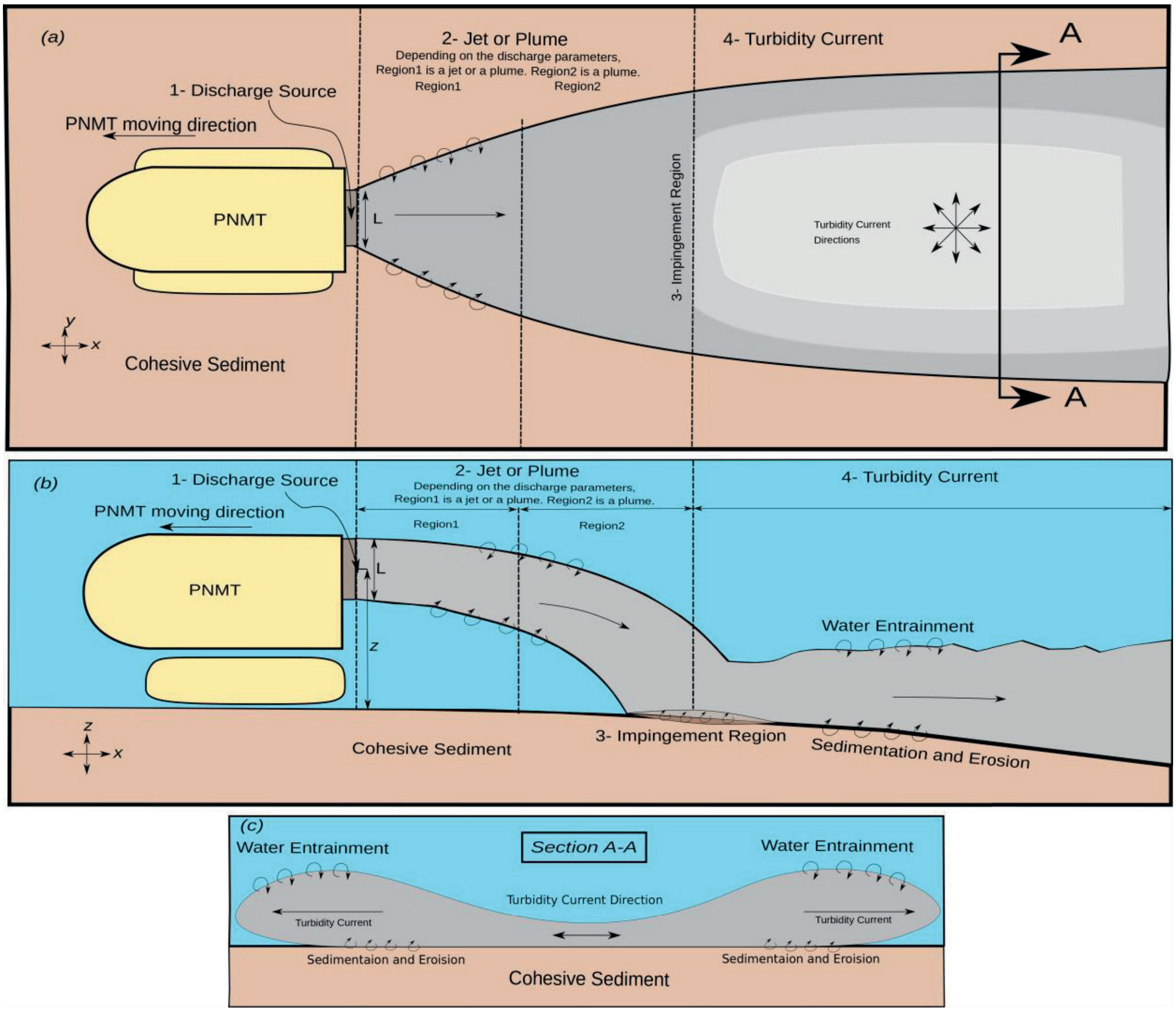

Figure 1. Conceptual sketch of the evolution of the sediment–water mixture discharged from a PNMT. (a) Top view of the discharge process from a PNMT. (b) Right side view for the discharge process from a PNMT (Elerian et al., 2021). (c) Section A-A shows the direction of turbidity current.

2 LABORATORY EXPERIMENTS

The physical properties that characterize turbidity currents is that a higher density fluid flows underneath a lower density fluid (Chowdhury and Testik,2011). Actually, it is hard to investigate the turbidity current in the field because of the limited resources (Georgoulaet al., 2010). However, there are alternative ways to investigate the desired parameters of a turbidity current. For example, it is possible to mimic the propagation of a turbidity current in the laboratory. Thus, one of the most common techniques of studying turbidity currents are lock-exchange experiments. These are about a sudden release of a fixed heavier fluid volume into a body of lighter fluid. Because of the generated buoyancy forces, i.e. the density difference between the two fluids generates buoyancy forces, the heavier fluid flows underneath the lighter fluid resulting a turbidity current. Through the propagation of the current, an entrainment process occurs at the boundary between the two fluids.

Particle size and initial concentration of the current play a major role in defining the deposition behavior of the current and thus the propagation velocity. Therefore, we test 3 sediment types with different particle size distribution. Moreover, in case of cohesive sediment, the flocculation between particles might contribute greatly to increasing the settling flux of the particles by increase particles mass. As a result, we investigate the natural flocculation (flocculation between particles without flocculating agents) and artificial flocculation (flocculation between particles with flocculating agents) effect on the propagation of the current (Table 1).

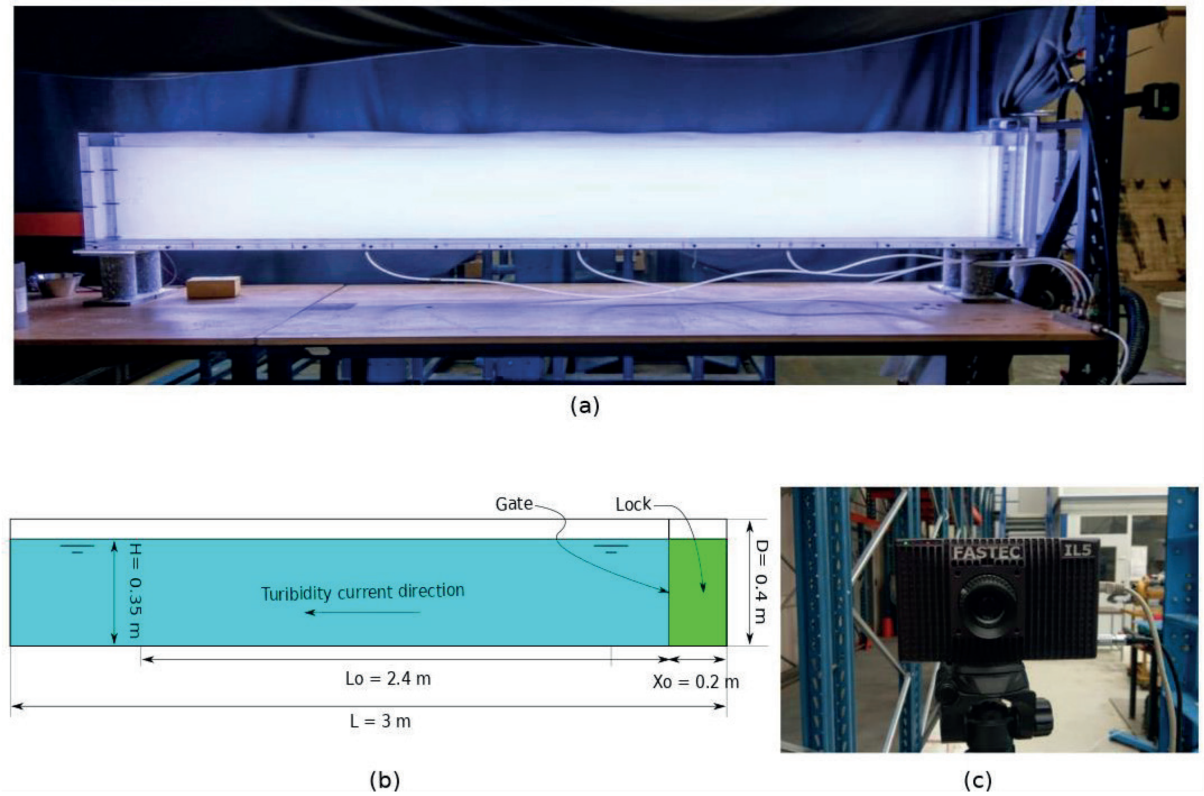

Figure 2. Lock-exchange experimental set-up. (a) Final set-up of the tank with the diffused light, (b) Schematic representation of the experiments, (c) The high-speed camera used for recording the propagation of the currents.

2.1 Experimental apparatus

Our lock-exchange experiment is based on a 3m long, 0.4m height, 0.2m wide Perspex tank. A gate is installed at 0.2m from the right side of the tank (Figure 2). Background plate with white led strips is positioned at the backside of the tank. A diffuse paper sheet is fixed in front of the white led strips to generate homogeneous light intensity. Furthermore, a black tent is installed over the entire experimental set-up to block out all ambient light. This enables recording of high speed/definition videos for different runs and repeatability of the runs. These videos are used to track the front position of the current in time.

The tank is filled with fresh-tap water to the height 0.35m at the beginning of each run. Then, the sediment is mixed at the lock with the water. Three non-cohesive and one cohesive sediment type are tested with different initial sediment concentration inside the lock. Since particle size, salinity and flocculating agents might cause a crucial change to the current propagation behavior. In this regard, Table 1 presents the main parameters for each experimental run. In case of salinity tests, CaCl2 salt is selected with a concentration of 1.1g/l, not to mention the salt is mixed in the whole tank before adding the sediment. Moreover, Zetag4120 is used as a flocculating agent (acting as a proxy for biological content), which is added and mixed only inside the lock, (i.e., Zetag4120 is a co-polymer of acrylamide and acrylic acid). The settling velocities mentioned in Table 1 is calculated using Ferguson and Church (2004) formula. For each run, we use high speed camera, type" IL5HM8512D Fastec" to record each run. The camera is placed 4.75 meters from the camera lens to the tank's front wall and films at a rate of 130 frames per second. The run starts when the gate is released, and turbidity current is formed. These videos are further used to track the current front position in time. The recording stops when the current gets out of the captured region (2.4m, Figure 1).

Table 1. Main parameters for the experimental runs

Runs	Sediment Type	Particle size[µm]	Mass [g/l]	Volume [%]	D50	Density of Particles	Salinity, CaCl2 [g/l]	Flocculating agents	Settling velocity [m/s]
1	Glass beads	65-105	12.28	0.5	88.6	2460	-	-	0.00137
2	Silica sand	4-60	6.64	0.25	17	2650	-	-	4.1 e-05
3	Silica sand	4-60	13.2	0.5	17	2650	-	-	4.1 e-05
4	50%Glass beads, 50%Silica sand	4-105	6.35	0.25	17 , 88.6	2460-2650	-	-	4.1 e-05 - 0.00137
5	50%Glass beads, 50%Silica sand	4-105	12.78	0.5	17 , 88.6	2460-2650	-	-	4.1 e-05 - 0.00137
6	Illite	1-20	10	0.36	4.9	2750	-	-	3.5 e-06
7	Illite	1-20	10	0.36	4.9	2750	1.1	-	3.5 e-06
8	Illite	1-20	10	0.36	4.9	2750	-	Zetag4120	3.5 e-06
9	Illite	1-20	10	0.36	4.9	2750	1.1	Zetag4120	3.5 e-06

3 RESULTS AND DISSCUSIONS

The most studied parameter for lock-exchange experiment is the front propagation velocity. By changing the initial condition of a turbidity current, e.g., sediment type, initial concentration, addition of flocculants, the current exhibits a totally different behavior. According to Huppert and Simpson, 1980; Rottman and Simpson, 1983, from the front speed of a current, we can distinguish three phases of a current namely, slumping phase, self-similar phase and viscous-buoyancy phase. Slumping phase occurs near the lock gate, where the front starts to form. Within this phase, the current is characterized with a constant propagation speed due to the balance between inertia and buoyancy forces. After that, the propagation speed of the current reduces, and this is what features the self-similar phase. Eventually, when the viscous forces dominate the current, the viscous-buoyancy phase takes place. In this respect, we investigate 4 main aspects as follows:

1. The effect of the particle size.
2. The effect of initial concentration.
3. The effect of salinity.
4. The effect of flocculating agents.

3.1 Non-Cohesive sediment

For the same initial concentration, the particle size can play a role in controlling the front velocity of the current. It is found that the current (silica sand) in run3 is faster by 40% from the current (glass beads) in run1 and by 24% from the current in run5 (mix of silica sand and glass beads, Figure 3 left). The same observation is noticed for in case of the comparison between run2 and run4 (Figure 3 right). However, the current in run2 is faster with only 16% than the current in run 4. This implies the effect of the particle sizes, where glass beads are larger in size and rounded in shape, while the particles in the silica sand are smaller in size and irregular in shape. This occurs due to the high settling velocity of the glass beads particles. In addition, because of the particle drag forces, the probability of the particle to be dragged into generated turbulence vortices is higher for silica sand, resulting the particles to stay in suspension, and then, more contribution to the generated buoyancy forces.

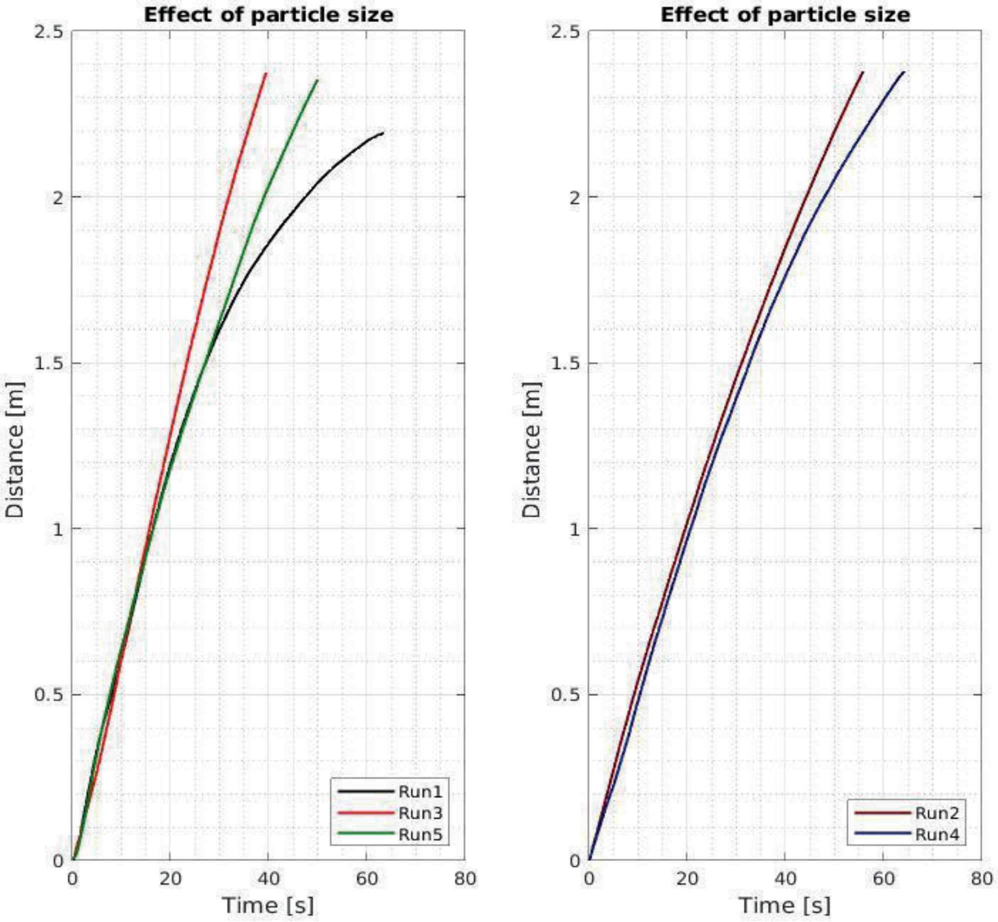

Figure 3. Effect of particle size on the propagation of the current.
Front position as a function in the propagation time.
Run1 is glass beads sediment, Runs2,3 are silica sand and Runs 4,5 are 50-50 glass beads and silica sand.

Not surprisingly that for the same sediment type, the higher initial concentration has a faster front speed than the lower initial concentrations. Doubling the amount of the initial silica sand mass would lead to 38% increase in the front velocity, while doubling the initial glass beads and silica sand masses would lead to 22% front velocity increase (Figure 4). The main reason behind this increase is that the presence of particles increases the generated driving buoyancy forces, and thus high front velocities. It can also be noticed that the percentage of the increase in the front velocity in case of silica sand (Figure 4, left) is higher than the mix of silica sand and glass bead (Figure 3, right). This can be related to the effect of the particle size, where the glass beads in sediment mix tend to settle faster and thus doesn’t contribute further to the buoyancy forces, unlike the silica sand.

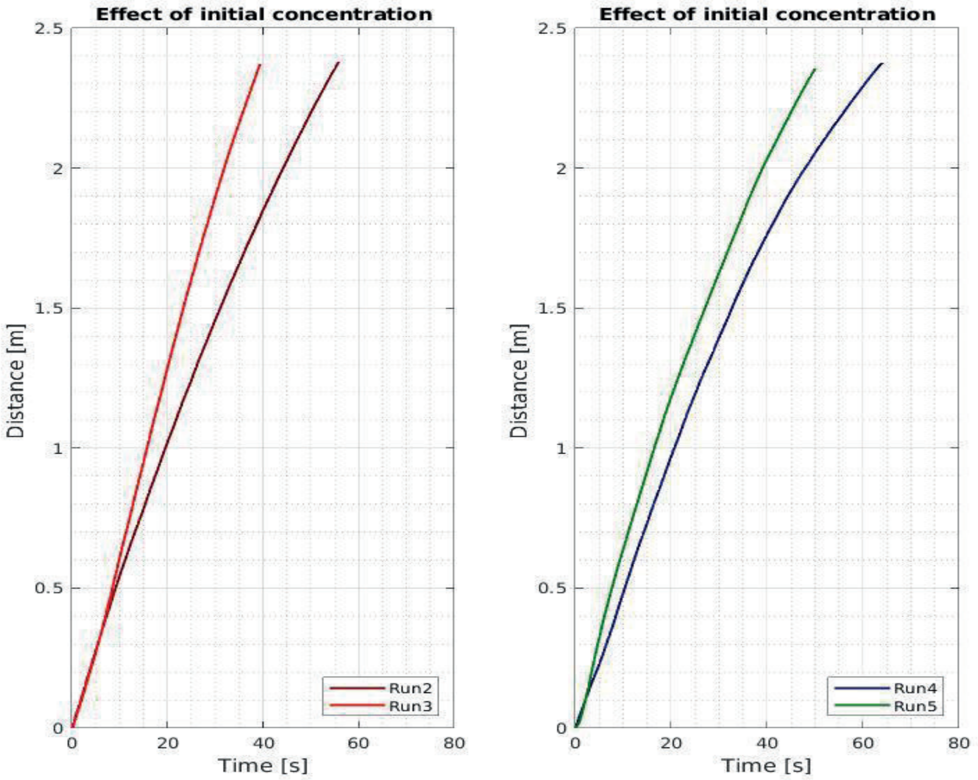

Figure 4. Effect of the initial concentration behind the lock on the propagation of the current. Front position as a function in the propagation time. 0.25% are the initial concentration for Runs 2,4, 0.5% are the initial concentration for Runs 3,5.

3.2 Cohesive sediment

Increasing particle size could cause higher settling potentials that would lead to shorter run out distances for the mining-generated turbidity currents. The dynamics of particles differ between cohesive and non-cohesive sediment. In case of cohesive sediments, as the particles collide together, and because of the cohesion properties of those particles, they tend to flocculate forming what is known as flocs. In fact, in some conditions such as high shear rates of the carrier fluid, these flocs can also break from each other and form small flocs or particles.

Illite is one of the most abundant clay mineral in the CCZ sediment, therefore we used illite as a cohesive sediment in our experiments, which consists of two silica tetrahedral attached to gibbsite octahedral. It is normally characterized by a negative charge on its plate-like surface. In the presence of water, the negative charge is basically caused by the substitution of Si-ions (Silicon) by AI-ions (Aluminum) in the silica tetrahedral sheet, then the K^+-ions (Potassium) comes into the inter layer to satisfy the charge and locks up the structure. In the absence of organic matter and in the presence of salt, the negative charges on the illite particles are neutralized by the existence of cations from the salt, i.e., calcium ions (Winterwerp & VanKesteren, 2004). As a result, the molecular Van der Waals attractive forces overcome the repulsive electrical forces induced by the negative charges on the particle's surface. Therefore, flocculation occurs much faster within the saline water than the fresh water. This can be observed on the comparison between run6 and run7 (Figure 5, left). As the current in run 6 (fresh water) is faster the current in run 7 (saline water) by factor 24%. This difference is a result of a fast floc formation in the saline water, and thus high settling potentials for the formed flocs. This means that in case of saline water, the generated buoyancy forces from the particles is lower than in fresh water. It is to be noted that the saline water density is slightly higher ($\rho_{saline} = 1001\, kg/m^3$) than fresh water ($\rho_{fresh} = 1000\, kg/m^3$). This implies that the density difference between saline water/ sediment mixture and fresh water/sediment mixture is almost the same, and thus the resulted difference in the propagation velocity is not related to the density difference.

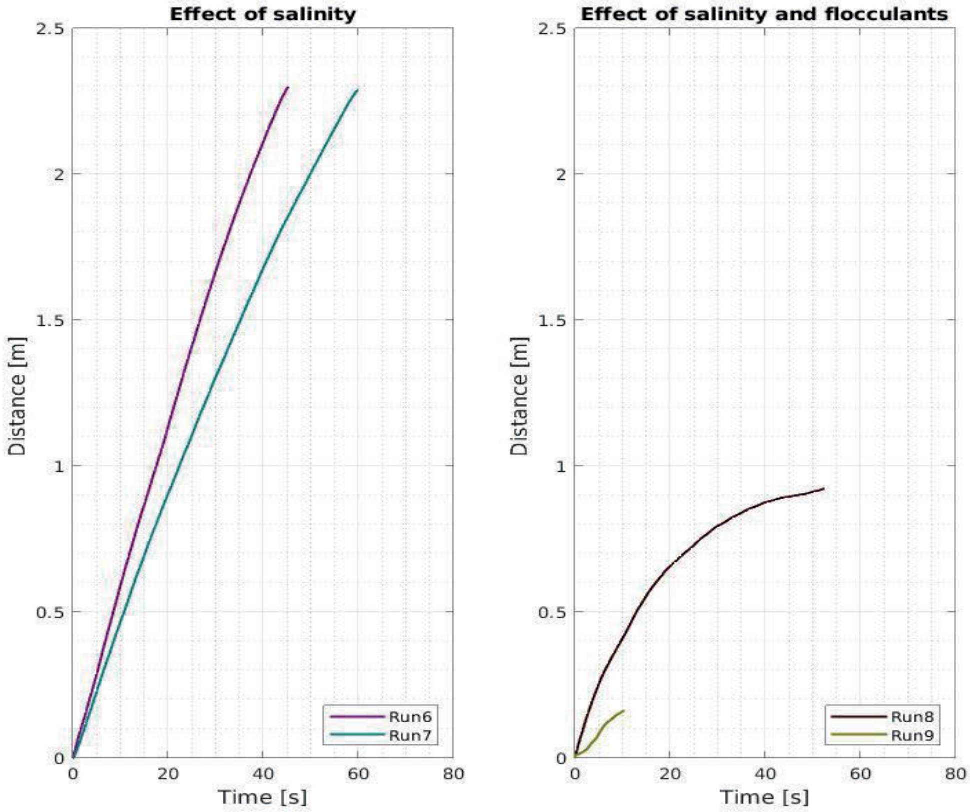

Figure 5. Effect of salinity on the propagation of the current. Front position is plotted against the propagation time. Saline water is used in case of Runs 7,9. Fresh water is used in case of Runs 6,8.

The above-mentioned mechanism of flocculation only occurs because of Van der Waals forces. However, in the presence of organic matter, two other forces contribute to floc formation, namely bipolar forces and hydrogen bonding. These two forces appear because of organic matter presence (Winterwerp & VanKesteren, 2004). Normally, the marine environment contains organic matter resulting from the biological processes of the fauna. Note that the bipolar forces are much stronger than Van der Waals forces, as the organic matter, i.e., polymers, clay particle interaction is not affected by the electrostatic repulsion. Hence, when the organic matter, i.e., polymer, is present, the clay particles adhere with the string of polymer at many locations, forming flocs. Moreover, because the water also is bipolar, these types of flocs structure bind large amounts of water. Moreover, organic matter entails humic acids with carboxyl groups and phenol-hydroxyl groups. These groups form hydrogen bonds easily with the clay minerals.

In this respect, in order to speed up the flocculation process, we used an anionic organic flocculating agent (Zetag4120), i.e., anionic polyelectrolytes, which is a co-polymer that contains chains of acrylamide and acrylic acid. Interestingly, form our observations, this polymer works very well in forming the flocs, since it is obvious that the currents in run8 and run 9 do not exceed the first 1 m and 0.5 m respectively of the tank and dies out (Figure 5, right and Figure 6, left). Although the anionic flocculant and illite particles are negatively charged, polyelectrolyte-mediated and adsorption flocculation occurs because of van der Waals attractions forces, hydrogen bonding and/or sporadic cationic sites on illite particles surface. These forces overcome the electrostatic repulsion forces. Not to mention the effect of salinity in run9, where the comparison between run7 and run9 (Figure 6, right) shows that the saline water has a significant impact on forming the flocs. This occurs because of presence of Ca^+ ions in the water that reduce the repulsion between particles and then increase the polyelectrolyte adsorption. In addition to that, Ca^+ ions provide anchoring and bridging sites for anionic polyelectrolyte molecules. Therefore, the flocs formation take place in a fast pace resulting an increase in the sediment settling, and thus the current driving force is reduced.

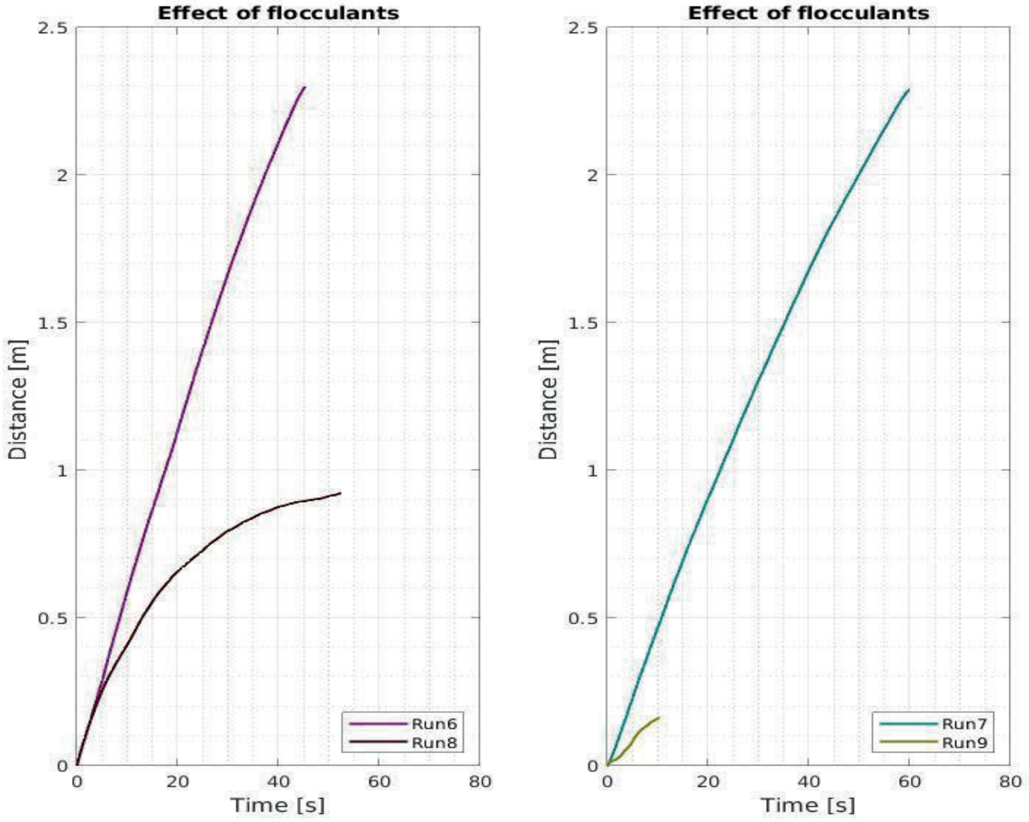

Figure 6. Effect of flocculants on the propagation of the turbidity current. Front position is plotted against the propagation time. Flocculating agents are used in case of Runs8,9. Flocculating agents are not used in case of Runs 6,7.

The above mentioned phases of a turbidity current, namely: slumping phase, self-similar and viscous-buoyancy phase, can be observed in most of the experimental runs. The straight line part of a distance-time curve represents the slumping phase where the velocity is constant. When the straight line starts to bend and to form a curve-like, this means that the current transitions to the self-similar phase. This implies that the current losses momentum and the velocity decrease. As the curve starts to bend more, this implies that the viscous forces starts to dominant and the current dies out. Based on this, it was observed that flocculating agents (runs 8,9 in Figure 5,6) speed up the transition time to self-similar and further the viscous-buoyancy phases. Moreover, increasing the particle size boost the transition as well due to the high settling velocities of the particles (Figure 3).

4 CONCLUSIONS

The turbidity current resulting from polymetallic nodules mining activities might cause significant impact to surrounding environment. Different parameters control the propagation behavior of these types of turbidity currents. In order to minimize the resulted negative impact, we experiment the effect of particle size, initial concentration, salinity and flocculating agents on the propagation behavior of the current.

Increasing particle size would cause low front velocities of the current, on the other hand, increasing initial concentrations results high front velocities of turbidity currents. Moreover, using illite as a cohesive sediment, the natural flocculation take place in saline water much faster than fresh water, where the forward velocity of the current in saline water is slower than the one in the fresh water. As anticipated, flocculating agents boost the flocculation process either in fresh or saline water. However, the flocculation process in saline water is much faster than the fresh water, since this is reflected on the front velocity of both currents.

These findings promote our understanding of the discharge process from a polymetallic mining tool. The aim is to speed up the transition time between the slumping to self-similar and further to the viscous-buoyancy phases. In order to do that, reducing the concentration at the discharge source might be beneficial. Additionally, flocculating agents might be an acceptable choice to increase flocculation potential in the near-field region. Moreover, the salinity level of the deep sea needs more investigations to quantify the flocculation process during the discharge.

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