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Research paper

Natural flocculation of mineral particles in seawater – influence on mine tailings sea disposal and particle dispersal

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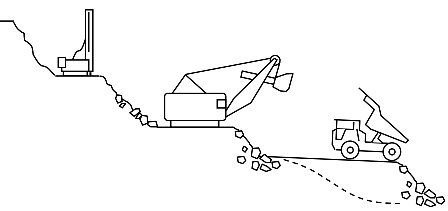
ABSTRACT

Mineral particles introduced in the marine environment form aggregates held together by Van der Waals forces and their ability to stick to dissolved and colloidal organic material. The aggregates or flocs account for the accelerated transport of suspended material to the seafloor. In low stress environments the size of flocs are large, in high stress environments the floc size is smaller. High particle concentration increases the flocculation rates. In many coastal sea environments, floc settling velocity ranges from 1 to 200 m/d with most flocs settling in the 10 to 100 m/d range. Observations made in natural coastal systems and fjords are relevant for sea disposal of mine tailings. As mine tailings may enter the sea as a particle slurry already mixed with seawater, the particles in the slurry are in the early stages of flocculation. The flocculation process will reduce the dispersal of fine grained tailings.



1. INTRODUCTION

Mining of minerals and metals creates huge quantities of fine grained tailings particles which have to be disposed (Apte and Kwong, 2004). In countries like Norway (Klif, 2010), Canada (Pedersen et al.,1995), USA (Alaska) (Kline, 1998), Greenland (Johansen and Asmund, 1999), Turkey (Berkun, 2005), Phillipines (Dold, 2006) and Papua New Guinea (McKinnon, 2002), DSTP (Deep Sea Tailings Placement) has been practiced for more than 30-40 years. In other countries, like Chile, sea disposal is now seriously being considered as an alternative to land disposal of tailings (Neira, 2012).

Lack of suitable land disposal sites as well as the location of ore resources close to the coast has increased the interest of exploring the possibility of DSTP. However, sea disposal is a politically sensitive issue and among NGOs and environmentalists strong opposition has been expressed. The main arguments against sea disposal of mine tailings have been the lack of control of the fine fraction of tailings (< 20µm), smothering of benthic ecosystems and the use of flotation reagents and chemical flocculation agents which are associated with the tailings. Unfortunately, there is a scarcity of published scientific documentation of the environmental implications of sea disposal of tailings. Most of the documentation is presently in the grey literature and in consultant reports.

This paper is not an argument for or against sea disposal, but rather points at some principal knowledge of natural processes in seawater which is very relevant when considering the fate of tailings particles disposed in deep estuaries like fjords etc. As tailings particles are ground up rock minerals similar to mineral particles being transported by rivers and glaciers, there are lessons to be learned from studies of the interaction between particle surfaces of minerals, seawater as an electrolyte and natural organic substances (debris from planktonic material, humic substances etc.).

One of the crucial processes which have effects on settling rates of particles and the residence time of clouds of fine particles in the water column, is flocculation. This paper is devoted to flocculation; the origin and composition of flocs, the settling of flocs and the implication of these processes on the anticipated environmental consequences of sea disposal of mine tailings. Syvitski et al. (1995) have shown that large flocs (>250µm) account for much of the particle-mass suspended in coastal water, and almost all of the mass-flux of particles settling to the sea floor in Halifax Inlet in Canada.

2. NATURAL FLOCCULATION OF MINERALS IN SEAWATER

2.1 Definitions and principles

When individual particles cluster together in the marine environment they are referred to as marine snow or flocs (Hurd and Spencer, 1991). The main types include (Syvitski and Murray, 1981): (1) strongly bonded aggregates, such as formed in soils; (2) agglomerates of more weakly held organic and inorganic matter; (3) planktonic fecal pellets; and (4) floccules of inorganic particles held together by Van der Waals force, after the electrostatic repelling forces associated with natural mineral grains are neutralized within a saline solution. Inorganic flocculation of silts and clays begins to occur at salinities between 3 to 5 ppt. Particles form clusters due to their inherent stickiness, their ability to adsorb dissolved and colloidal material, and their interaction with microbes and plankton

(Syvitski et al., 1985). They account for the accelerated transport of suspended material to the seafloor.

Sea water is a perfect environment for clustering individual particles — the water is of high salinity (>30 ppt), and is rich in both particulate and dissolved organic matter. Aggregation theory (for review see Syvitski et al., 1995) simplifies the problem to two conditions: 1) whether suspended particles are able to come into contact with one another, i.e. the encounter problem, and 2) whether the particles stick when an encounter occurs, i.e. the attachment problem. The main encounter mechanisms are differential settling (large particles sinking quickly will sweep up the smaller particles), and laminar or turbulent shear where differences in fluid velocity cause two particles carried by the fluid to approach each other. High particle concentration helps both encounter mechanisms. Differential settling dominates in low turbulent conditions. For typical marine conditions the attachment probability (stickiness) is very high (approaching 1.0; Syvitski et al., 1995).

In general the effect of suspended concentration on sediment settling is that: 1) flocculation rate increases with the suspended particle concentration; 2) rapid sediment loss occurs at high concentration, and 3) settling leaves slower sinking particles in suspension. In low energy environments the size of flocs is large, in high energy environments the floc size is smaller.

2.2 Floc characteristics

Individual particles in seawater may be characterized by filtration and use of scanning electron microscopy and elemental analyses by X-ray fluorescence (Skei, 1991). When it comes to flocculated particles they will normally not survive the water collection and the filtration process.

In situ measurements of marine particles, based on quantitative camera techniques (e.g. Syvitski et al., 1995) can readily define marine particle characteristics. In situ images go through threshold mapping, edge detection and particle mapping to locate each unique particle. Each particle or floc then has their aspect ratio (D_{max} to D_{min}) determined, and the numbers of particles-per-litre are binned into particle size intervals to develop number-concentration spectra (Fig.1). If sequential images are collected then particle tracing allows for the settling velocity of each floc, and their settling Reynolds number and their particle Drag coefficient to be determined. These values are needed to determine the equivalent spherical sedimentation diameter, the excess floc density and thus the porosity of each floc.

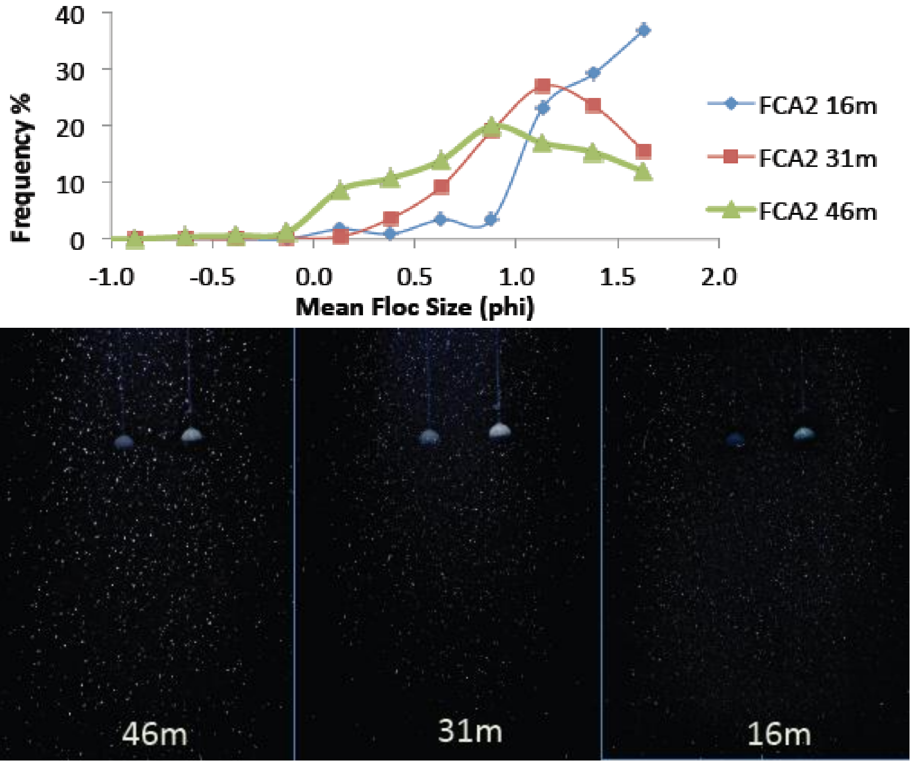


Figure 1. Number concentration spectra from the St. Lawrence Estuary through the upper part of the water column. The in situ images correspond with each water-depth particle spectra.

In general flocs form within a river plume and then settle through the halocline and into the deep-water column below this brackish water lens. In a fjord, the particles are elongated (ellipsoids), with a settling Reynolds number often above 1 for the larger (>1000 µm-size) flocs. The settling velocity of a floc often depends on its diameter, with larger flocs settling one or two orders of magnitude faster than smaller flocs. In many coastal sea environments, floc settling velocity ranges from 1 to 200 m/d with most flocs settling in the 10 to 100 m/d range (Syvitski et al., 1995). While it is not possible, based on diameter to predict accurately the settling velocity of a single floc, it is possible to estimate the mean settling velocity of a population of like-sized flocs (Hill et al., 1998). As the flocs form, they incorporate much seawater and thus have floc porosities typically greater than 0.90 with most particles being greater than 0.99.

The relationship between excess-floc density (i.e. the difference in density between a suspended particle (floc) and the ambient fluid) and particle size depends on constituent properties (mineral matter, phytoplankton, bacteria). A particle's mass depends on the excess-floc density and these values are used to convert the particle number spectra to a mass concentration spectra. Once the mass of each floc size class is determined, along with the floc concentration spectra (see Fig.1), and the settling velocity of each floc size class, then the floc sedimentation rate can be calculated.

A study in Disenchantment Bay, Alaska, demonstrates that fine sediment beneath a meltwater plume is flocculated and that floc sizes and the fraction of mass bound within flocs exhibit a pronounced increase with depth rather than down fjord distance. This spatial pattern of variability is likely due to the longer depositional timescale of settling flocs compared to their horizontal advection timescale within the meltwater plume (Curran et al., 2004).

Figure 2. Floc Camera Assembly in-situ image of flocs in seawater (from image library of JPM Syvitski collected in Goose Bay, Labrador). The image shows a resuspension plume stirred up from the floc camera hitting the seafloor (bottom left). Above and to the right is the ambient background seawater containing flocs settling.

Figure 2 shows an image of a resuspension plume emanating from the seafloor. The material resuspended contains very fine-grained material (hazy white cloud) of individual particles, and clumps/aggregates of seafloor mud shown as dark blotches within the cloud. The image is informative for showing that while particles settle through the water column as flocs (see the background surrounding particles settling through the water column), these flocs become degraded on the seafloor. Thus bacteria essentially liberate the constituent particles within a floc when they are left to age on and within the seafloor. In addition grazing organisms (e.g. benthic copepods) can repackage these constituent particles into fecal pellets. Other geochemical processes may also partially cement the individual particles once on the seafloor.

2.3 Turbidity Currents

As mine tailings may enter the sea as a particle slurry already mixed with seawater, the particles in the slurry are in the early stages of flocculation. Also, given the high-suspended sediment concentration in the seawater slurry, it is likely that particles enter the marine environment as a hyperpycnal plume otherwise known as a turbidity current. The final condition of note is that the outlet pipe, that releases the tailings slurry is often placed well below the surface layer of the fjord. Thus the discharge plume will enter the fjord environment as a turbulent jet, entraining seawater into the resulting plume and thus diluting the slurry as it spreads laterally and sinks towards the seafloor. Dilution of the plume will continue until the plume reaches the seafloor where the material will move into deep water as a bottom boundary layer flow. If the seafloor is steep, the turbidity current could ignite (begin to travel faster) by adding more sediment to the flow from seafloor erosion than is being deposited through sedimentation (see Parsons et al., 2007 for overview). Turbidity currents will deposit sediment based on the settling characteristics of the particles. Nearer the tailings outlet, the coarser particles will settle out, with only a smaller fraction of the fines. Further away from the pipe, finer grained particles will deposit.

A variety of numerical models are available to rather accurately predict the sedimentation pattern beneath a turbidity current (Syvitski et al., 2007). The application of these models to a tailings-generated turbidity current is limited to our knowledge of how fast the particles of different grain size will settle out of the plume, and that is partly based on the flocculation dynamics of tailing material. We speculate that the size of the flocs within a tailings turbidity current will be limited, as the level of turbulent shear will be high, too high for the formation of large flocs. However, there is little evidence to suggest that the tailings particles would not flocculate.

3. SEA DISPOSAL OF MINE TAILINGS

3.1 Background

Large scale mining operations may handle 5-50 million tonnes of mine tailings per year. This is due to the fact that the mineral or metal mined often represent less than 5% and sometimes less than 1 % of the ore body. In the case of sea disposal the tailings from the thickener pass a mixing tank where sea water is mixed in at a ratio between seawater and freshwater in the tailing pipe of 2:1 to 6:1 (Pedersen et al., 1995). This will increase the density of the slurry when it leaves the tailings pipe and the plume will sink towards the bottom, gradually losing its density due to settling out of coarse particles and mixing with seawater with low levels of particles. De-aeration of the tailings is also important to avoid entrapment of air bubbles which may transport fine grained particles to the surface. Even if the majority of the tailings move as a near bottom plume, a certain plume splitting may occur where a cloud of very fine tailings particles are entrained higher up in the water column, often associated with a small break in the water density. The question is if the concentration of tailings particles in this cloud exceeds levels causing any risks or problems for the pelagic ecosystem. This concentration will depend on the flocculation rate and rate of settling of flocs to the bottom and the dilution with seawater with background concentrations of particles.

3.2 Environmental implications

There are different opinions about the environmental risks related to elevated levels of mineral particles in seawater. Naturally, the levels of particles in surface waters in fjords vary considerably on a seasonal basis, particularly if the rivers are carrying large quantities of silts and clay (Skei et al., 2003). In fjords influenced by glacial flour extraordinary high levels may occur in the melting season (Syvitski et al., 1987). Glacial flour is freshly ground up minerals and is quite similar to mine tailings from a physical point of view (roundness of particles, freshly exposed mineral surfaces etc.). If the tailings contain needle-like minerals, this has been considered as a potential problem for fish (damaging fish gills) (Lake and Hinch, 1999).

Flotation in mining requires large quantities of a range of chemicals. Most of the chemicals are harmless, degradable and show little toxicity. To what extent these chemicals may influence natural flocculation is uncertain. Starch is often used in large quantities and may enhance the bacterial activity in the receiving water and thereby increase the level of organic matter and indirectly increase the flocculation efficiency (see 2.1).

Little attention has been paid to natural flocculation in seawater regarding mine tailings disposal. The mining industry uses chemical flocculants in the thickener to recover fresh water. Flocculants may also be added to the tailings pipe to increase the formation of flocs and to inhibit large scale dispersal of tailing fines. If it is documented that seawater is an efficient natural flocculent for tailings particles, the use of chemical flocculants may be reduced. This has both environmental and economic benefits. However, scientific documentation is necessary to prove the efficiency, not only laboratory experiments (Fig.1), but also use of in situ Floc Camera Assembly (see 2.2) to obtain visual documentation of the in-situ size, shape, concentration and settling velocity of tailings particles. This provides insight into the in-situ excess density, porosity and mass of flocs, their population characteristics, and aggregation and sedimentation rate (Syvitski et al., 1995).

3.3 Prediction of sedimentation and dispersal of tailings

When sea disposal of mine tailings is preferred to land disposal, the following assumptions are made:

- The buffer capacity of seawater prevents pH problems (acid generation) when sulfide tailings are disposed.
- Tailings solids that might oxidize and generate soluble heavy metals on land will not oxidize to the same extent on the sea floor.
- Following closure of the mine and termination of tailings disposal, natural sedimentation of inert minerals and organic debris will create a new soft bottom habitat for benthic animals.
- By utilizing best available technology (BAT) regarding disposal infrastructure it is anticipated that the disposal site has a limited geographical extent (efficient sedimentation). The selected disposal area should be a sedimentation basin and not an erosion site, with a minimum degree of resuspension and particle dispersal.
- Seawater also reduces the zeta potential (a measure of the effective surface charge that a solid particle suspended in water carries) on solids to near-zero, causing coagulation and agglomeration of tailings particles (Apte and Kwong, 2004).

The last take home message is the focal point in this paper. How can we predict that a slurry of tailings particles with a grain size varying between sand and clay will deposit within a planned disposal site? Coarse particles will build a conical pile near the end of a tailings pipe. By time the angle of the pile exceeds the stability, the pile will collapse and the sandy tailings will spread over a larger area.

A cloud of fine particles will be dispersed by gravity for a while until the density of the cloud is reduced to reach buoyancy. From then on the cloud is dispersed by bottom currents and during deep water renewals, which may take place annually in fjord basins (Syvitski et al., 1987). The particle cloud may be lifted to shallower depths, depending on the seasonal hydrographical stratification. It is expected that flocculation takes place in the particle cloud due to collision between particles when the particle density is high. The flocs settle rapidly towards the bottom, but due to decreasing particle density the mechanism of flocculation diminishes. According to Pedersen et al. (1995), the particle cloud which splits off the tailings plume will quickly reduce its particle content to levels which have little environmental consequences.

4. CONCLUSIONS

Processes of natural flocculation of mineral particles in association with organic substances in seawater enhance particle removal from the water masses to the sea bed. Due to the stability of the flocs where mineral particles stick to organic slime, resuspension of the sediments is less predominant compared to sediments of the silt and sand fraction where the mineral grains settle as individual grains. Flocs can degrade on the seafloor and this increases the chance of being resuspended, but still when compared to a completely non flocculated environment the seafloor is a more stable substrate. There will be a greater chance of resuspension from the lake bed as the particles are not flocculated and therefore they are more readily mobile than when compared to a fjord or seafloor environment.

When tailings particles from mining activities, with a grain size of less than 10 µm, are disposed through a pipeline in a deep fjord, a similar process of flocculation will take place, preventing a substantial dispersal of fines from the disposal area. Additionally, formation of flocs in association with natural organic matter will reduce the turbidity of the water and the potential environmental risks.

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