Bio-Engineering for Sediment Management And Removal of Turbidity Technologies: BESMART Technologies

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Publication date
2020

Document Version
Final published version

Published in
Terra et Aqua

TECHNICAL

BIO-ENGINEERING SEDIMENT MANAGEMENT AND REMOVAL OF TURBIDITY TECHNOLOGIES: BESMART TECHNOLOGIES

All these bio-abiotic interactions have widely been observed in nature and discussed in scientific publications by Deltares, and also worldwide.

At Deltares in the Netherlands, a research team is developing a portfolio of technologies dedicated to the management of the finest and most challenging fraction of soft sediments. These technologies may unambiguously be called nature based because they make use of natural processes to enhance dewatering and strengthening, induce flocculation and the settling of fines, and protect the muddy bed from erosion.

Some of these technologies are already at an advanced stage of research and development, the reason that we can already report about them. For the present, the team refer to the portfolio of innovations as the Bio-Engineering and Sediment Management And Removal of Turbidity Technologies (BESMART Technologies) portfolio, though this has led to confusion. This research at Deltares explicitly does not involve techniques associated with classical biotechnology, such as gene manipulation or genetic engineering. The approach may be seen as holistic, and it does not interfere with nature but attempts to bring about a synergy with it.

The weakness of the naming of this research is presently a topic of discussion, but we do not want it to interfere with a presentation of the natural technologies that have already been brought to market or that will soon be ready for application. Examples of these technologies are:

- worms for soft sediment dewatering and strengthening;
- algae as a bio-flocculant;
- Kaumera® as a bio-flocculant;
- *Beggiatoa* (bacteria mats) as bed protection; and
- vegetation for mud dewatering, strengthening and bed protection.

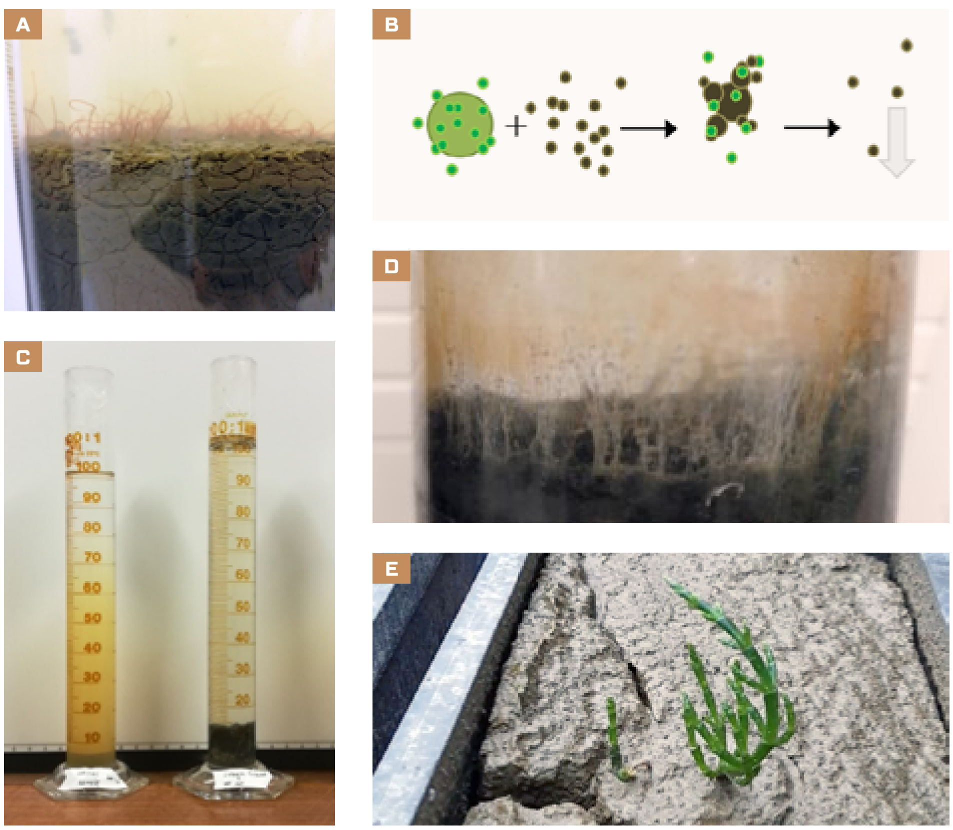

FIGURE 1

Overview of the BESMART Technologies as discussed in this article: (A) Worms for soft sediment dewatering and strengthening, (B) algae as a bio-flocculant, (C) Kaumera® as a bio-flocculant, (D) Beggiatoa (bacteria) as bed protection and (E) vegetation for soft sediment dewatering, strengthening and bed protection.

FIGURE 2

Deposition of soil in a land reclamation project (https://publicwiki.deltares.nl/display/BTG/Strategically+placing+mud)

Over the coming sections each of the technologies in the portfolio will be discussed, and their technological goal introduced.

All these bio-abiotic interactions have widely been observed in nature and discussed in scientific publications by Deltares, and also worldwide. Ours is an on-going and thus far successful attempt to make use of these natural processes for achieving engineering goals.

Current sediment management techniques can be improved

Soft sediments are mixtures of fine sediments (clay and silt), water and organic matter with a high water content. Typically, these soft sediments have a consistency ranging from chocolate milk to yogurt. Worldwide, soft sediments are transported and deposited in the context of mining operations, maintenance and capital dredging in ports and navigational channels, land reclamation projects, and beneficial reuse of sediment applications. Soft sediment, and sediments generally, therefore play a key role in human development activities. Pressure to use and reuse locally available resources (i.e. the circular economy), to work towards climate mitigation and adaptation, the development of nature and on resilient and sustainable infrastructures demands an optimal and integrated management of these sediment flows.

Though they are extremely common in industrial and engineering operations and are potentially a precious resource for sustainable development, these soft sediments present significant management challenges. Varying feed properties and segregation of the coarse and fine fractions cause heterogeneity of deposits, and consequently varying consolidation, strength and total settlement characteristics. The finest, low-dewatering and low-strength fraction poses the greatest challenges. In re-suspension soft sediments are typically easily erodible, and once brought into suspension in the water column its fines exhibit their characteristic large residence time and associated turbidity issues.

There are several traditional measures to overcome these sediment management issues. First, there is the use of flocculants and chemicals to induce flocculation and the settling of a suspension, but also to thicken and strengthen soft sediments. Second, carrying out sediment re-working hardware interventions, like physical compaction, to increase the strength of soft sediments and minimise the re-suspension of fines. Finally, applying geo-textiles and other types of bed protection to control the erosion of fines. Typically, these measures are labor intensive and therefore expensive and environmentally impacting.

Scientists from Deltares are developing innovative and naturally based technologies dedicated to the management of the finest and most challenging fraction of these soft sediments. These technologies make use of natural processes to enhance dewatering and strengthening, induce flocculation and the settling of fines, and protect the muddy bed upon deposition of the soft sediments. These are all being developed under the umbrella of the same research initiative, the BESMART Technologies portfolio. Apart from their obvious savings (these interventions are mostly natural and therefore passive) and environmental care, these technologies all take a real and sound technical ability to solve sediment management issues as their starting point. In fact, they all have a very specific technological goal. Over the coming sections each of the technologies in the portfolio will be discussed, and their technological goal introduced.

A final important point of consideration is that the integration in the local ecology of the system is a necessary condition for considering any of our technologies.

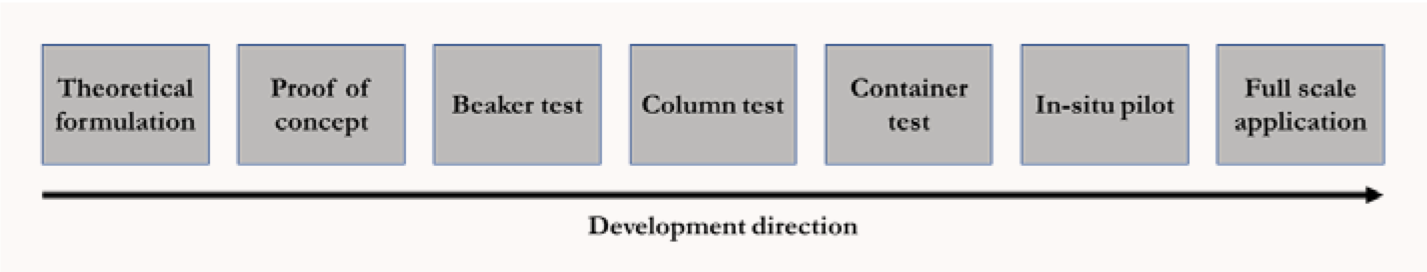

FIGURE 3

The technological development cycle.

The technologies may not make use of non-endemic biological factors, and their development must ensure either a safe continuation or even the restoration of the main ecological functions of the system. Bypassing biological manipulation and investing in ecological integrity is therefore an axiom of the fine BESMART Technologies portfolio.

The seven steps of the technological development cycle

The technologies discussed here are the products of a technically sound research process. Their efficiency has been demonstrated in a laboratory setting, and they are now transitioning into intermediatescale and even full-scale application. Others have, however, only successfully completed the proof-of-concept tests. And other technologies are still in the phase of theoretical formulation but have been included in this overview given their consistency with the philosophy of the portfolio. To cover all the different stages of development that our technologies undergo, we have defined the following phases of what we call the technology growth cycle. All the introduced technologies are currently at one of the following development phases:

- Theoretical formulation of a sediment management bio-technology, based on observations of biotic-abiotic interactions in nature (e.g., plants strengthening a soil via their root development);
- Proof of concept in a laboratory. The objective of the proof of concept is to qualitatively demonstrate that the technology has an impact in the targeted engineering goal. In other words, its aim is to turn the theoretical formulation into a simple and qualitative laboratory test;
- Beaker tests to quantitatively assess the performance of the technology. Once the proof of concept has confirmed that the technology can deliver an engineering goal we set up a number of small beaker tests of approximately 0.5 l in volume per beaker to make a first assessment of the parameter space best suited for the technology to attain its engineering goal;
- Column tests of larger (but still smaller than in application; for example, approximately 2-20 l of soft sediments) sediment volumes, for in-depth analysis of the engineering performance of the technology for a selection of initial parameters as determined by the beaker tests;
- Container tests of relatively larger volumes of soft sediments (in the order of 1 m^3 or 2 m^3 to study spatial effects and effects for greater depths. This is also where operational considerations like the application method start playing a role;
- On-site pilot test to evaluate the performance of the technology under field conditions, including the feasibility of the method when integrated into the existing engineering or industrial operations; and
- Full-scale application.

BESMART Technologies compared with nature-based solutions

It is necessary to position BESMART Technologies in relation with the popular nature-based solutions discipline which is currently subject to many research and application studies. Nature-based solutions can be defined by their use of natural processes to realise hydraulic infrastructure. Moreover, the development of a nature-based solution is often accompanied by the ecological restoration of the system. BESMART Technologies on the other hand are focused on one particular engineering process helping us to realise an infrastructure, but may not be the actual infrastructure itself. And though it needs to be respectful of

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local ecological dynamics it does not aim for ecological restoration per se. This becomes more explicit when defining examples of nature-based solutions and BESMART Technologies in contrast with their grey engineering equivalents. A nature-based solution could, for example, be a vegetated foreshore (to lower the height of the design of a dyke next to it), and its grey equivalent would be a higher dyke. A BESMART Technology could be the effective strengthening of soil under trees against erosion, with its grey equivalent being mechanical soil compaction or the placement of a geo-textile. The goal of the nature-based solution is to protect the coastline, while the goal of a BESMART Technology applied similarly is simply to strengthen the bed at the shoreline (which ultimately can address a coastal safety goal and also a water quality goal via a decrease in sediment re-suspension and turbidity). BESMART Technologies are thus meant to either replace or optimalise certain engineering processes such as compaction, dewatering, bed protection and flocculation but not necessarily to become hydraulic infrastructure.

FIGURE 4

Image of an oligochaete worm population at the waterbed interface of soft sediment. The tunnels made by the worms that help to dewater the soft sediment are visible through the glass.

Worms for soft sediment dewatering and strengthening

Applying natural worms to soft sediment deposits enhances dewatering and the strength of soft sediment deposits. This is the most advanced technology within our portfolio when positioning it on the technological development cycle, as it is currently transitioning from large column tests to container scale, and as there are already concrete discussions about a potential future pilot with some of the involved stakeholders. The technology is inspired by observations of natural sediment dynamics in Dutch water bodies, where oligochaete worms were found to qualitatively speed up dewatering of freshly deposited soft sediments (de Lucas Pardo, 2014). The basic principle is that worms, which feed on the organic matter present in the soft sediments, produce tunnels within the soft sediment matrix, enhancing dewatering. Worms appear also to change the geochemical structure of the soft soil matrix with their biological functions, enhancing strength. The type and amount of organic matter in the sediment influences the behaviour of the worms. Here we define two types of soft sediments, based on the availability of organic matter in them:

1. derived from industrial operations with very little organic matter, for example, from mining operations. In this article we call this 'tailings'; and
2. organic-rich sediment from natural systems that was transported because of engineering activities, for example, from deepening navigational channels or from land reclamation projects. In this article we call this 'natural sediments'.

In tailings, organic matter is scarce and worms must travel up and down the sediment throughout its entire thickness, seeking suitable food. This results in a tunnel network through the entire layer of soft sediments which creates a substantial increase in its hydraulic permeability, notably speeding up dewatering. The disadvantage of applying worms in this type of soft sediment is that they die from starvation after few months, ending their favorable effect on the sediment. The initial research phases for the use of worms to dewater tailings were published by Yang in 2016 and 2019 in research projects led by Deltares scientists. In natural

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sediment where organic matter is abundant, worms stay in the uppermost 15 to 20 cm of the bed. Worms survive indefinitely in this type of soft sediment, but their beneficial effect is confined to the uppermost centimetres of the bed. Optimalising conditions for the worm-enhanced dewatering in these two types of soft sediments requires different approaches.

In tailings with little organic matter worms were demonstrated to increase solid content from 43% to 61% in only one month (for a layer of 30 cm of soft sediment in the laboratory). This is equivalent to an increase in the soft sediment's bulk density from 1,350 kg/m^3 to greater than 1,600 kg/m^3. Without worms, self-weight consolidation of the exact same type and volume of tailings would result in a final 52% solid content, but after approximately three months. This means that the increase in solid content with worm treatment is 100% greater relative to how many more are absent, and it happens in one third of the time. This positive effect is explained by the tunnels that the worms dig throughout the entire thickness of the soft sediment when seeking food, which becomes an easy and fast route for water the escape the bed, therefore speeding up dewatering and strengthening.

Yet worms start dying in tailings after one month due to food scarcity, and end up disappearing after approximately a month and a half. To overcome the problem of limited food for worms in tailings, the Deltares research team incorporated into the tailings a small portion of easily available and cheap organic matter, such as straw or hay. The amount of matter added is approximately 0.5% in mass of the solids in the soft sediment. This organic matter is uniformly distributed throughout the entire thickness of the soft sediment. In real operations this would necessitate, for example, the injection of small amounts of hay where the soft sediment is discharged from the pipe. When organic matter was added to the soft sediment, worms reproduced by a factor of 3 after 4 months. This method should be a way to increase the beneficial dewatering and strengthening effect of worms over time. In fact, preliminary results from on-going laboratory experiments at Deltares suggest that the highest dewatering rates result from adding organic matter to tailings.

Preliminary exploratory tests in natural soft sediments dredged from a European port revealed that in only 3 days worms can lead to the dewatering of 15% of the initial volume of soft sediments. This is a high daily dewatering rate when compared with the results in tailings, taking into account the fact that the previously reported increase of solid content was equivalent to almost 40% of the initial volume of the soft sediments but needed more than 30 days to develop. This is particularly remarkable when compared with the 0% compaction that the soft sediments exhibited in the absence of worms. A 0% dewatering after a few days under self-weight consolidation is not that uncommon, given the capacity of certain clay minerals and certain organic matter types to form large aggregates with a very high water content, which are unlikely to lose water and compact.

FIGURE 5

A scientist at the Deltares sediment laboratory setting up laboratory experiments on worm dewatering of tailings.

In the presence of worms however, significant dewatering did not occur after the initial 15%. The worms, which initially travelled up and down the entire thickness of soft sediments to explore and adapt to their new environment, slowly started to concentrate at the surface over time, where we presume they found everything they needed to live. Therefore in natural sediment with more organic matter, the challenge to optimalise the effect of worms on dewatering the soft sediments is fundamentally different. In this type of environment worms do not experience food scarcity and live indefinitely, but their action is confined to the top of the soft sediments and therefore their beneficial effect becomes limited. Recent testing in other types of natural sediment collected in other industrial contexts indicates an even higher performance of the worms following the optimalisation and adjustment of the worm density to the characteristics of the local mud. Finally, a worm re-worked bed has very recently also proved to dewater (or ripen) via evaporation in a more rapid and efficient manner as the result of a dense tunnel network in the upper region of the bed.

To prevent the worms' concentrating at the surface of natural sediment, and to optimalise their effectiveness as a dewatering tool, the Deltares research team have engineered a new solution similar to that applied in tailings. It is easily available and uses cheap organic matter mixed with the soft sediments. This time it was not distributed throughout the entire thickness, but placed at depth in the soft sediments. Assuming that added food is desirable for the worms, researchers strategically place the matter such that it motivates the worms to dig tunnels over the entire depth of the soft sediments, likely achieving similar long-term performance as in tailings. The latter is currently being tested at the Deltares sediment laboratory and will soon be evaluated as a technical possibility for managing soft sediments at important European ports.

Worm-enhanced dewatering of soft sediments is therefore a promising sediment management technology that displays very competitive results in the laboratory and also contains the promise of being an engineering tool that is free of chemicals and minimises carbon emissions in sediment management projects. Subsequent research efforts, which are already being developed, will address its suitability for field applications, and build upon the success collected at the laboratory phase.

Algae as a bio-flocculant

The second BESMART Technology is the application of algae to flocculate fines in the water column to ultimately solve potential turbidity issues. Adding phytoplankton to a turbid water column is a feasible and viable alternative method for enhancing flocculation and sedimentation rates of suspended cohesive sediment. In particular, this technology has been tested for oil sands tailings via the execution of a proof of concept in the laboratory. Phytoplankton do not only rapidly form large aggregates (de Lucas Pardo et al., 2015), but they also increase the capacity to capture and precipitate the finest sediment fraction. Numerous species of phytoplankton have the tendency to flocculate with suspended cohesive sediments. *Aphanotece* sp. is a cyanobacteria (a sub-type of algae) endemic to natural bodies of water worldwide that revealed that it could form large flocs and induce sedimentation in very turbid bodies of water (de Lucas Pardo et al., 2015). This was shown over a number of experiments, where *Aphanotece* sp. was mixed with suspended cohesive sediment. When the phytoplankton and sediments were vigorously mixed, plankton-clay flocs reached an equilibrium floc size twice that of flocs without the plankton, surpassing the maximum theoretical size that a floc can reach for a given turbulence level (e.g. creating extraordinarily large flocs for such conditions). When mixed under moderate energy levels, the large plankton-clay flocs cannot be kept in suspension anymore, thus settle.

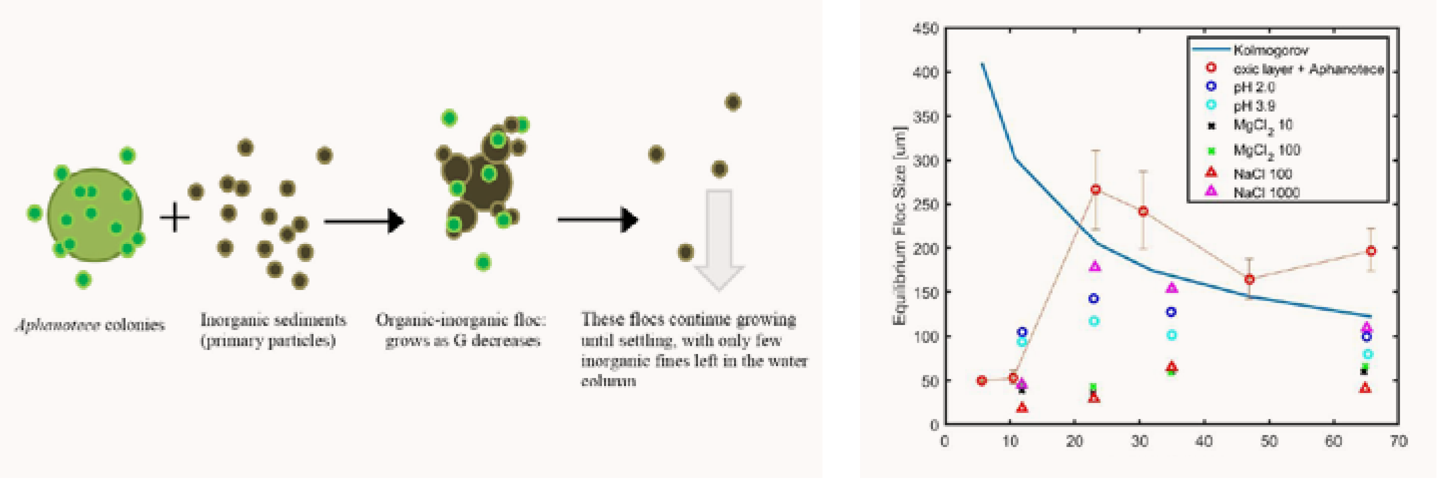

FIGURE 6

The left panel summarizes the results from de Lucas Pardo (2015), where extraordinarily large flocs (red dots) are obtained for a mixture of algae and sediment (oxic layer is just surficial lacustrine sediment). All other markers represent salt induced flocculation, and results in smaller equilibrium floc sizes than algae. The right panel shows a conceptual picture of the aggregation between algae and fines.

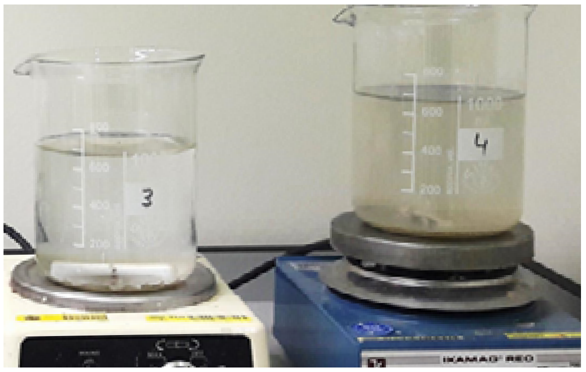

FIGURE 7

Comparison between algae treatment (beaker 3) and the absence of it (beaker 4). Both beakers contained a concentration of 250 mg/l of suspended tailings. Beaker 3 also contained a concentration of $1*10^5$ cell/ml (i.e. a very small concentration) of *Aphanotece* sp. algae. The picture was taken after gently mixing at a minimal energy level and after allowing for settling after mixing. The differences in turbidity after treatment are striking.

These are results that illustrate the extraordinary physical features of biotic-abiotic flocs summarised in the left panel of Figure 6 and conceptualised in the sketch in the right panel of Figure 6; the actual mixing level needed in the field to achieve optimal results is yet unknown. Moreover, the study also showed that the rate at which aggregation occurred was much faster when plankton were present. *Aphanotece* sp. is organised in colonies, with its individual cells being 1 to 2 µm. This allows the cyanobacteria to form large but flexible colonies embedded in extracellular polymeric substances (EPSs). The EPS gives the colonies its ability to bind to clay particles, whereas the small size of the individuals enables colonies to change shape and adapt to specific inorganic floc shapes. The catching capacity of *Aphanotece* sp. can be studied and hereafter adjusted, so that *Aphanotece* sp. can be used to a range of fines concentrations. Our plans are to subsequently scale up our test to beaker volumes and to study the flocculation capacity of similar species of algae with natural fines or suspended tailings in a jar testing set-up, where turbulence level can be adjusted to resemble field conditions and potential mixing methods. Furthermore, the EPS around algae can bind dissolved cations from the water column and this requires further research. Finally, it is not well known for how long these large biotic-abiotic flocs persist. The durability of these flocs will therefore become a subject of future studies.

Over the past years Deltares has studied this technology by funding the development of a proof of concept. The context of this proof of concept was oil sands tailings management, in particular turbidity mitigation at what are called end pit lakes, where thick oil sands deposits are capped by a fresh-water lake. Suspended oil sands tailings concentrations of 125 mg/l and 250 mg/l were efficiently flocculated and settled upon gently mixing (at the minimum mixing energy allowed by our mixing instrumentation) with a small concentration of *Aphanotece* sp. algae of $1\ 10^5$ cells/ml. A picture of the jars from the 250 mg/l tests at the end of the test is shown in Figure 5.2. Our preliminary conclusion is that suspended tailings were efficiently settled upon treatment with algae. Further analysis confirmed that in the absence of algae, flocculation and settling did not happen (see Figure 3). Note that typically occurring concentrations of *Aphanotece* sp. in natural water bodies are of about $50*10^7$ cells/ml (de Lucas Pardo et al., 2015), 5,000 times higher than the tested concentration.

Natural lakes with similar algae concentrations could provide a cheap and large input of flocculant if found within a transport range that is financially attractive. An alternative source in the absence of lakes within reasonable distances would be to cultivate the algae on site, which according to our expertise should be feasible both technically and financially. Considering that higher concentrations occur in both culturing reactors and natural water bodies than the concentration we tested, the potential of the technology to treat a water column in tailings ponds and/or pit lakes becomes a tangible and attractive possibility.
We also foresee similar efficiencies in dealing with turbidity in other types of systems, or with natural sediment. Not only is this a fully natural solution, but its performance is also competitive. When produced on site, we recommend adopting the bulk-type culturing reactor, which though subjected to episodically low performances can on average provide the type of high concentrations needed for this application. Producing algae in a local reactor could be a competitive alternative to expensive chemical flocculants. Finally, mixing the algae

FIGURE 8

Comparison in turbidity between algae treatment (right) and the absence of it (left).

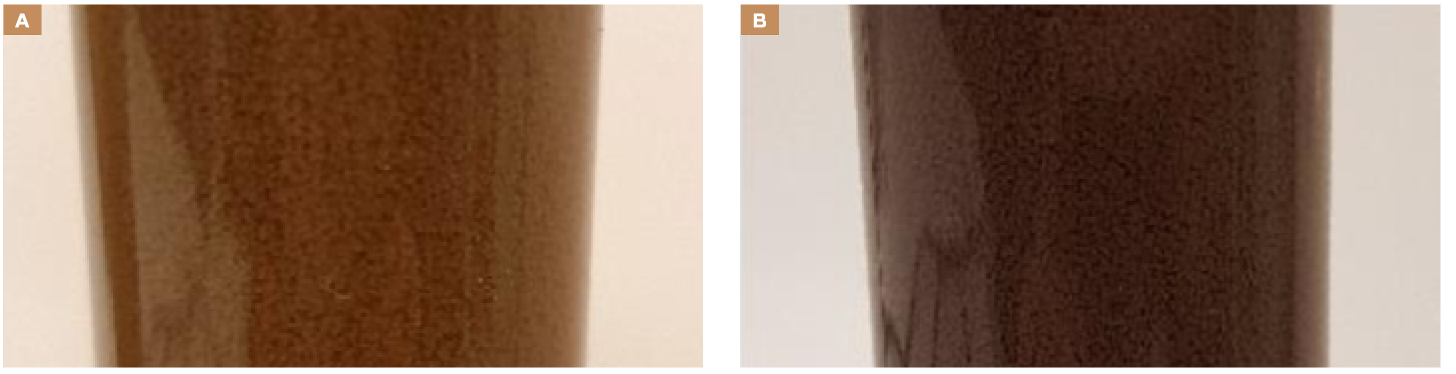

FIGURE 9
Floc created (A) 2 minutes and (B) 30 minutes after addition of Kaumera® to tailings.

obtained with tailings in the field can be done by depositing them under a mixing engine from a pontoon.

To conclude, the technological performance of bio-flocculation by algae has been successfully tested at the laboratory scale, via a proof of concept (and the associated knowledge and research generated at our laboratories). Subsequent research steps should consider carrying out column to container experiments, seeking to quantify the performance of algae when they are studied for the operational parameters of a selected stakeholder.

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Kaumera® as a bio-flocculant

Kaumera® is an Extracellular Polymeric Substance (EPS) extracted from aerobic granular sludge from the Nereda® waste-water treatment process. 'Kaumera' is a word in the Maori language that can be translated as 'chameleon' (https://kaumera.com/). Delft University of Technology (TU Delft) in the Netherlands is leading the development of the process of the extraction of Kaumera®, and is currently also looking for a wide scope of applications for a new bio-based raw material that is extracted during the Nereda® purification process. Specialized in sediment characterization and conditioning, Deltares collaborates with TU Delft in finding uses for sediment management applications with Kaumera®. This collaboration came to be over the course of several proofs of concept in our research.

Kaumera® is biodegradable and therefore can also be used as fertilizer or as a food source for other organisms (e.g., worms), thus ultimately preparing sediment for biological development. The technology of using Kaumera® to manage fine sediment has the same applications as our algae technology (e.g., flocculation and turbidity mitigation, discussed previously), plus the possibility to biologically improve the properties of settled sediment. The bio-flocculant can potentially help sediment management projects to enhance the consolidation properties of dredged sediment (since adding Kaumera® leads to a drop of pH, which can affect the surface charge of clay particles and ultimately modify its consolidation behavior and strength development) and to decrease turbidity of water columns in natural muddy bodies of water.

The potential of Kaumera® as a bio-flocculant for tailings has been evaluated during a proof of concept that consisted of flocculation experiments (Wyszynska, 2020). Figure 9 shows the development of flocs that was observed in the sample containing Kaumera® 2 minutes and 30 minutes after adding the bio-flocculant to 1 wt% tailings sample. Though not visible in the reported figure, the experiments also showed that the turbidity of the supernatant obtained after the addition of Kaumera® was better than the one for the control sample.

Successful flocculation experiments in the form of proof of concept have also been conducted for stable clay mineral suspensions. Pure 1 wt% kaolinite and 1 wt% bentonite clay samples were used for testing the effectiveness of Kaumera®. The left panel in Figure 10 illustrates a clear difference between the flocculation of kaolinite and bentonite with Kaumera®. A radical improvement in the flocculation of bentonite has been detected. The formation of a more compact bed and lower turbidity of the supernatant is observed in a Kaumera-treated bentonite sample. The flocculation tests on the kaolinite sample show that the bio-flocculant improves the settling of kaolinite clays. The thickness of settled mud is more pronounced in the Kaumera-treated kaolinite sample than in a control sample. The change in the color of Kaumera-treated supernatant is attributed to the addition of the Kaumera® extract. This proof of concept can be applied to predict and understand flocculation of natural sediments, and as a function of their dominant clay mineral.

Finally, Kaumera® was also evaluated as flocculant for suspended fines at a mining operation in a river near Medellín, Colombia. The mining operation consists of dredging of the alluvial sediment at confined river sections. The turbidity at these sections was a severe environmental issue, and thus Deltares developed a proof of concept to test the efficiency of Kaumera® in flocculating the suspended river sediments. The right-hand panel in Figure 10 shows the results of conducted laboratory experiments with Kaumera®. The sample in the middle was treated with Kaumera®. The other two samples were not treated and thus constitute two replicates of the reference situation. The suspended sediment concentration was 10 mg/l in all three samples. Kaumera® successfully managed to flocculate and settle the small concentrations of fines.

Overall, the proof of concept experiments show that Kaumera® can potentially be used as a bio-flocculant to help sediment management projects. The bio-flocculant has a great potential to expand the portfolio of applications, especially for tailings management since tailings are mainly considered a waste product with no economic value. Raising awareness of environmental impacts might limit the use of chemical flocculants in the future. Because Kaumera® is bio-degradable, the development of Kaumera® as a bio-flocculant can lead to environmental benefits in sediment management projects. Combining this bio-flocculant with other technologies discussed in this paper is considered promising for the biological development of treated sediment.

Beggiatoa (bacteria) as bed protection

The engineering goal of *Beggiatoa* technology is to protect muddy beds from erosion by currents or waves, thus stopping re-suspension events and the generation of turbidity. We envision this technology to be best suited for contaminated sediment deposits (upon successful results from our on-going proof of concept research and subsequent research phases) where anoxic conditions have developed right under the top centimetres. This happens because anoxic (or near anoxic) conditions are necessary for *Beggiatoa* to establish and survive. Due to these particular requirements, there are few ecosystems or waterbodies where the bacteria might be applied. Of course the technology can still be applied as an intermediate mechanism for restoration in systems that are suffering from ecological deterioration, but its application would not be ideal at a hypothetical restored configuration. The technology is currently transitioning between a proof of concept and a column study.

Sulfide (S_2–) oxidizing bacteria of the genera Thioploca and Beggiatoa form dense mats in the top layer of the sediment bed, both in marine and freshwater sediments (Teske and Nelson, 2013). The organisms typically oxidize hydrogen sulfide (H_2S) as an electron donor into elemental sulfur (S_0; which is stored inside the bacteria's cells) with oxygen (O_2) or nitrate (NO_3–) as electron acceptor. Sulfide oxidation detoxifies the sediment, creating better habitat for other organisms to grow. In nature both genera occur at the oxic-anoxic interface, preferably in micro-oxic to anaerobic conditions (O_2 0-2,5 µm). Furthermore, they are photophobic, requiring dark conditions for growth (Teske and Nelson, 2013).

Because Kaumera® is bio-degradable, the development of Kaumera® as a bio-flocculant can lead to environmental benefits in sediment management projects.

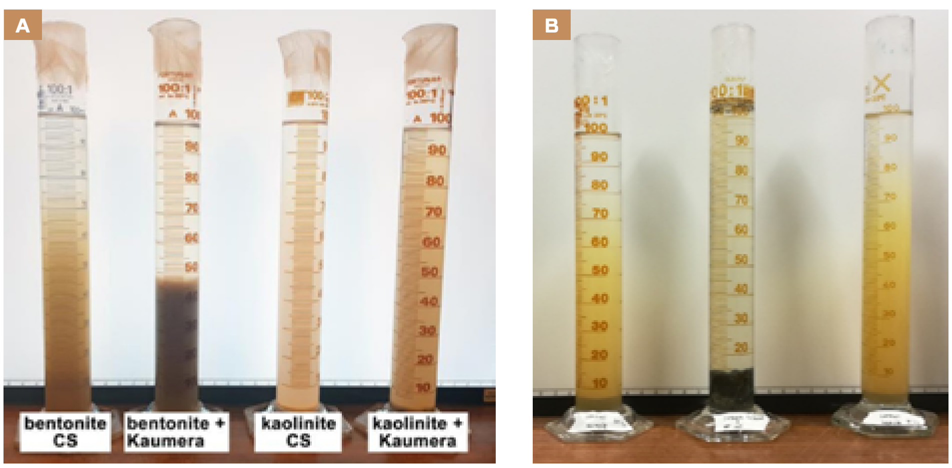


FIGURE 10

(A) Flocculation experiments of bentonite and kaolinite clay suspensions containing 1wt.% of clay minerals. The bentonite control sample (CS) shows higher turbidity than Kaumera-treated bentonite sample. Furthermore, there is more kaolinite clay settled in the graduated cylinder with Kaumera-treated sample than in the one with the kaolinite control sample (change in the color of Kaumera-treated supernatant is attributed to the addition of the Kaumera® extract). (B) The results of using Kaumera® to flocculate suspended fine sediments from a river mining operation. The sample in the middle was treated with Kaumera®. The other two samples were not treated and thus constitute two replicates of the reference situation. The suspended sediment concentration was 10 mg/l in all three samples.

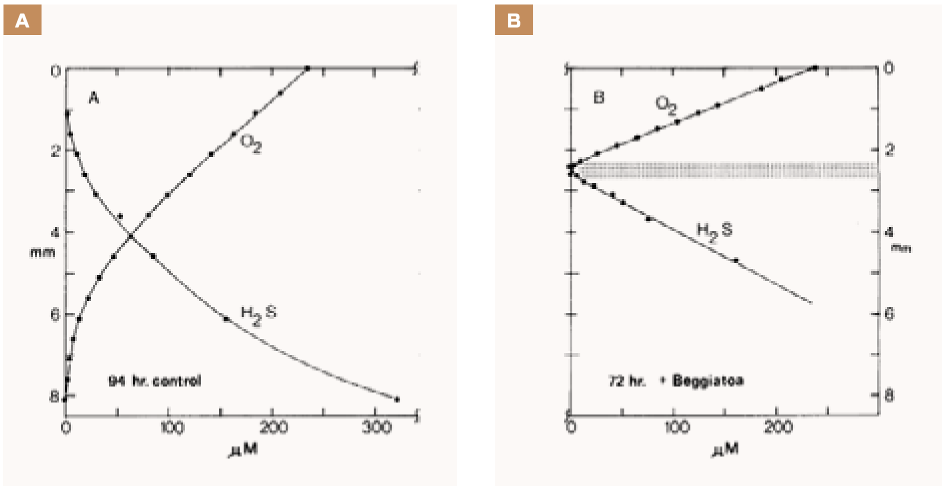


FIGURE 11

Showing the oxygen (O_2) and hydrogen sulfide (H_2S) concentration (μM) along the depth (mm) in a control medium (A) and created by Beggiatoa (B) after 3 days in this medium. Zero depth indicates the air-plate interface. The grey area shows the location of the Beggiatoa mat in the medium. (Source Teske & Salman 2014; Nelson et al., 1986).

What is so special about these bacteria is that they both grow as filaments, vertically in the sediment and can glide from an electron acceptor (O_2 or NO_3-) to an electron donor pool (H_2S), giving them competitive advantage over non-mobile microorganisms that use the same resources. Due to their metabolism these organisms strongly contribute to separating an electron acceptor from the electron donor pool (Nelson et al., 1986). Because of these advantages, their filamentous growth can form dense mats, from a few millimetres thick (as observed in Markermeer, the Netherlands) up to several centimetres (only observed in the ocean floor). Mat thickness appears to depend on dynamics and the stability of the sulfide/oxidant interface (Teske and Nelson, 2013). It is precisely to the mat and its thickness that we attribute the bacteria's function in protecting the bed.

Within Deltares, sediment strength with and without natural sulfide oxidizer mats was tested in resuspension experiments (Kauhl, Roskam and Noordhuis, internal communication). Sediment was collected from the lake Markermeer, where natural dense mats of sulfide oxidizers occur. Sediment with dense sulfide oxidizer mats showed greater strength and could withstand higher shear stress before resuspending than sediment without these mats (see Figure 12). Also, sediment with bacterial mats displayed maximum erosion rates at a higher shear stress. These preliminary results show that sulfide oxidizer mats in sediments can strengthen a fine sediment bed. Developing such mats in natural sediment therefore can contribute to a decrease of erosion from muddy beds and its associated turbidity in the waterbody, and can thereby improve water quality. Therefore, the BESMART Technologies research team has initiated both a proof of concept and a set of column tests to prove its efficiency in addressing sediment management issues. The proof of concept consists of trying to grow *Beggiatoa* mats in sediment beds where it did not naturally occur. Upon the finalization of a successful proof of concept, the subsequent step will be to quantify the bed's enhanced strength and its greater resistance to erosion in dedicated geo-technical and erosional tests (e.g. column tests level in the technological development cycle).

Vegetation for soft sediment dewatering, strengthening, and bed protection

Aside from the BESMART Technologies, there is also a bio-technology that has the potential to dewater and strengthen soft sediments and protect the bed: vegetation. However, to use vegetation to dewater, strengthen and protect soft sediments and muddy beds is still in a theoretical formulation phase at Deltares. Currently, Deltares is investigating how soil strength, affected by water and clay content, influences salt marsh plant dislodgement and stability under wave impact (see Figure 13). The inverse phenomenon, how plants affect soil properties, has not been studied explicitly in our laboratories yet. Notwithstanding, investigations at the Northern Alberta Institute of Technology (NAIT), Deltares' partner in on-going research projects, revealed that plants can distinctly influence dewatering oil sands tailings (Schoonmaker, Degenhardt and Floreani, 2018). Currently, the synergistic

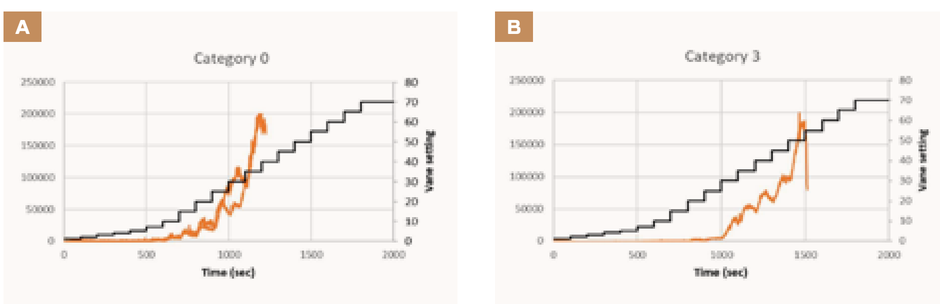


FIGURE 12

The increase in turbidity (left Y-axis in non-calibrated turbidity units; turbidity increases as the units do) over time (X-axis in seconds) in orange, with black being the stepwise increase of the vane setting every 100 seconds (right Y-axis in non-calibrated shear units; applied shear increases as the units do). Sediment in category 0 contains no sulfide oxidizer mat. Sediment in category 3 contains a well-developed mat.

performance of both worms and plants on dewatering is under investigation via the execution of a collaborative project between NAIT and Deltares. Because of the potential that vegetation has in assisting with sediment management issues, and also because the BESMART Technologies research team is interested in contributing to the development of this topic, lessons learned from our partners and existing insights from literature will be shared in a concise literature review. It can be seen as our own theoretical formulation of this technology's potential to assess sediment management issues. This review derives from the balance between entrainment in the water column and retainment in the bed, to the dewatering and therefore strengthening potential of (ripened) soils.

Plants change the environment with their physical structure. They are often referred to as autogenic ecosystem engineers (Jones, Lawton and Shachak, 1994) acting in a marine environment (Crain and Bertness, 2006) and fresh-water environments (Jones, Lawton and Shachak, 1997). Their role is that of slowing down currents and attenuating waves (Coppenolle, Schwarz and Temmerman, 2018; Ghisalberti and Nepf, 2006; Norris, Mullarney, Bryan and Henderson, 2017). This results from the generation of turbulence around their roots, stems and leaves, dissipating hydrodynamic energy. This makes soils less susceptible to erosion. In these locations of hydrodynamic tranquility, fines are captured from the water column by roots, trunks and stems of the vegetation, inducing the transition from particle entrainment to its retainment in the bed.

By dissipating hydrodynamic energy, vegetation protects the bed from erosion, but plants also contribute to the strength of the soil itself. Root networks hold together the sediment particles fortifying soils up to the breaking point of the root network. The tensile strength of the roots differs per species, which affects to what extent they contribute to its soil strengthening capacity. For example, *Spartina ssp.* builds stronger cliffs compared with *Limonium ssp.* because the roots of *Spartina ssp.* have a higher tensile strength (van Eerdt, 1985)

Once a soil is substantiated after an initial settling phase, vegetation aids in mediating dewatering by means of evapotranspiration

FIGURE 13

Pioneering plant species Salicornia ssp. are grown in boxes containing different sediment compositions. Ultimately, these seedlings are tested in a wave flume to quantify critical wave energy and erosion per sediment type. These tests will give insight into which locations are suitable for Salicornia recruitment mediating salt marsh growth. The newly sprouted salt marsh will provide ecosystem services like capturing fines, aerating and dewatering the soil.

(Smith, Banks and Schwab, 2009). Evapotranspiration is the sum of evaporation and transpiration of the vegetation and soil. Settlement can take place in nature or upland consolidation depots in which evapotranspiration contributes to expel water from the soil, inducing crack formation, which can open up the soil for oxidation processes. Moreover, plants contribute to mixing soil particles (Pons and Zonneveld, 1965), aerating the soil with oxygen, fostering oxidation (Trapp and Karlson, 2001) and removing pollutants (Duggan, 2005; Smith et al., 2009).

Plants can contribute substantially to dewatering. For example, dewatering in an upland depot with soil-plant systems with willow species was 1.28 times, up to 5.12 times, higher than control sections (Białowiec, Wojnowska-Baryła and Agopsowicz, 2007) marked by high transpiration ability-is a cheap and effective method of landfill leachate disposal. A two-year study examined the effectiveness of leachate evapotranspiration from soil-plant systems with willow species S. amygdalina L. Evapotranspiration from soil-plant systems planted with willow was from 1.28 up to 5.12 times higher than evaporation from soil surface barren of vegetation. This proves the usefulness of soil-plant systems with willow in landfill leachate treatment through vaporization. Evapotranspiration efficiency, as opposed to total amount of water added into the lysimeter, was not strong enough to vaporize all input of the landfill leachate in the lysimeters. This may indicate that the ground water requires isolation when soil systems remain under landfill leachate irrigation. Linear dependence between willow biomass growth and transpiration was observed to be significant ($p < 0.05$. Willow species are promising dewatering agents. In search of sustainable, environmentally passive and inexpensive methods to remove leachate, evapotranspiration by willows is viewed as promising in Sweden (Börjesson and Berndes, 2006) and the U.K. (Duggan, 2005).

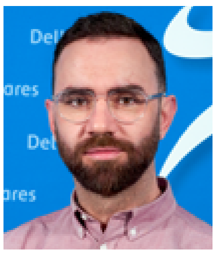
Therefore, given the potential of vegetation to protect the bed from erosion, to provide strength to the soil via its root network and to efficiently dewater the bed's pore water, vegetation will be subject of upcoming studies at Deltares. The subject of these will be to quantify dewatering and strengthening potential and also bed protection potential. These quantifications will take place over a range of laboratory experiments, evolving as always from proof of concept to column tests and further. The first step will be to identify a stakeholder who owns a fine sediment management issue where this technology can be of use, as it was the case with all other BESMART Technologies.

Continuing development of promising sediment management technology

BESMART Technologies are a promising alternative to traditional sediment management measures for dealing with the challenges of fine sediment engineering operations. All of them have been proven in the laboratory to be effective in achieving their engineering goal within the targeted operational range. Deltares has itself carried out numerous laboratory experiments, ranging from proof of concept to column tests, to demonstrate this. So far it has covered all the BESMART Technologies named in this article with the exception of vegetation. Some of these technologies are either application-ready or require fine-tuning before application. Yet other technologies still require research and their method further validation. Many private partners worldwide are teaming up with Deltares either to develop these ideas or to test their applicability for particular engineering problems. Slowly, we foresee that the technologies will become part of our partners' standard operational practice, allowing for a smooth transition from applied scientific development to practice.

Cost-effectiveness, technical performance and integration in the local ecosystem are the main principles for the application of BESMART Technologies. Nevertheless, and though the BESMART Technologies team at Deltares strongly believes in the secondary advantages of this method (low impact and low emissions given their passive nature), we will only consider and develop ideas that are based on sound engineering and technological development.This research is based on the collaboration between various international academic and private institutions. Therefore we invite the interested reader to reach out with potential dedicated applications or scientific improvements to facilitate scale-up of these technologies to implementation.

For more information or enquiries, please contact editor@iadc-dredging.com



Dr Miguel de Lucas

Dr Miguel de Lucas is a Senior Adviser at Deltares in the Netherlands. He holds an MSc in Hydraulic Engineering from UPM of Madrid and TU Delft, and a PhD in fine sediment dynamics from the TU Delft. During his PhD, Dr de Lucas began to study feedbacks between biotic and abiotic factors in the context of fine sediment transport. The latter materialised into commercial research projects at his subsequent position in Deltares where he leads the BESMART Technologies research team.

Dr Alex Kirichek

Alex developed a strong background in soil mechanics and rheology during his MSc degree in Civil Engineering (cum laude). After his graduation, Alex conducted multidisciplinary PhD research in Applied Geophysics at TU Delft, where he developed novel geophysical surveying methods. Later, he carried out postdoctoral research, testing cost-effective maintenance strategies for ports and waterways with mud. Currently, Alex is working as a Researcher/Adviser at Deltares, bridging the gap between applied research and practice.

Dr Martine Kox

Dr Martine Kox is a Junior Research/Adviser at Deltares, in the Netherlands. She completed an MSc degree in Environmental Biology at Utrecht University and obtained her PhD in Environmental Microbiology at Radboud University. During her PhD, Dr Kox studied the ecology of microorganisms occurring in peatlands, focusing on greenhouse gas emissions and nitrogen cycling. Within Deltares Martine applies her knowledge of microbiology to improve sediment characteristics, water and health and reduce greenhouse gas emissions.

Floris van Rees

Floris van Rees is a Junior Researcher/Adviser at Deltares, in the Netherlands. He started exploring the career path of a bio-geomorphologist during his Master's degree in Physical Geography at Utrecht University and continued studying bio-physical interactions at Deltares. Floris van Rees is involved in numerous sediment management bio-tech studies and one-to-one scale modelling of reciprocal actions between plants, waves and sediment.

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