Improving Engineering Properties of Mature Fine Tailings using *Tubifex*

Xiaojuan Yang[1, 2], Miguel de Lucas Pardo[3], Maria Ibanez[4], Lijun Deng[5, *], Luca Sittoni[3], Ania Ulrich[5], Qun Chen[2]

[1] PowerChina Huadong Engineering Corporation Limited, Hangzhou 311122, China

[2] State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource & Hydropower, Sichuan University, Chengdu 610065, China

[3] Deltares, Ecosystem and Sediment Dynamics, Postbus 177, 2600 MH Delft, the Netherlands

[4] Antea Group, Roderveldlaan 1, 2600 Antwerpen, Belgium

[5] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, T6G 1H9, Canada

* Corresponding Author: Department of Civil & Environ Eng, University of Alberta

6-261 Donadeo Innovation Centre for Engineering

9211 116 St., Edmonton, AB, T6G 1H9

Tel.:+1 780-492-6210; E-mail address: ldeng@ualberta.ca

Abstract: The present study investigated the effects of *Tubifex* treatment on the dewatering process of mature fine tailings (MFT). Experiments testing the survival rate showed that *Tubifex* can survive at 20 °C and 4 °C. MFT with 30 wt% initial solids content (S_c) was treated in eleven settling columns by three *Tubifex* densities, 1400, 2000 and 4200 individuals/m^2 respectively. Test results showed that the average survival rate at 20 °C and 4 °C on the 28th day stayed around 85%. *Tubifex* enhanced MFT dewatering by providing compacted tailings with 11.6% and 66.7% higher S_c and undrained shear strength than non-treated tailings. *Tubifex* accelerated pore water pressure dissipation. *Tubifex* did not affect other chemical composition of tailings except for the decrease of sulfate content. Tailings treated by *Tubifex* increased by 67.4 % increase in S_c within nine months, which was 129% greater than S_c increase of the non-treated tailings after eleven months.

Key words: MFT, *Tubifex*, dewatering, solids content, pore water pressure

INTRODUCTION

Northern Alberta has the third-largest petroleum reserve in the world in the form of oil sands (Alberta Energy 2014). Of all the oil sands reserve, about 10% has an overburden depth less than 65 m, which could be extracted by surface mining technology (Jeeravipoolvarn 2010). In the Clark Hot Water Extraction process, warm to hot water, aeration, and reagents are used to separate the bitumen from oil sands matrix. Two barrels of water for each barrel of bitumen is required, which results in a significant quantity of oil sands tailings (Entezari 2016). The latest industry data indicates that there are nearly 1 billion m^3 tailings accumulated in the ponds occupying a total area of 176 km^2 (Wang et al. 2016). The large volume of tailings constitute a major challenge to land reclamation, may contaminate the groundwater and surface water to a large extent, and may render the risk of tailings dam failure. Thus the Energy Resource Conservation Board (ERCB) developed new tailings management regulations in 2009; one of the key requirements is that the dedicated disposal areas must be trafficable and ready for reclamation eventually (BGC 2010). However, without extra human interference it would take excessively long for mature fine tailings (MFT) under self-weight consolidation and for land reclamation.

A number of techniques have been tested to accelerate the dewatering and tailings remediation, including physical processes, chemical amendment, natural processes, and biological treatment (Powter et al. 2010; Liang et al. 2015). In recent years, cost-effective and environment-friendly bioremediation and biodensification process have been preferred. It was demonstrated that indigenous microorganisms in tailings ponds facilitate the biodegradation of the naphthenic acids, biosorption of heavy metals, and sulfate reduction (Herman et al. 1993; Wolfaardy et al. 2008). The addition of microbes tends to separate the organic carbon from particles, enhances the settling and improves the water quality (Brigmon et al. 2016). Siddeque (2014a; 2014b) reported that the microbial community could accelerate tailings consolidation by reducing the surface charge potential (and thus reducing repulsive forces) of the clay particle; in addition, because of the bubbling up of biogenic gases during the microbial reaction, transient channels were formed that accelerated the pore water dissipation. The mixed culture of two microbial species together with rhamnolipid biosurfactant were applied to enhance the tailings sedimentation and bioremediation without producing large amounts of CH_4 (Mulligan et al. 2016).

A new, eco-friendly method using *Tubifex* worms has been recently tested for the accelerated treatment of oil sand tailings. Indigenous in Western Canada provinces, *Tubifex* worms have shown to be effective in reducing the volume of municipal sludge (Huang et al. 2007) and speeding up the rate of consolidation of very soft estuary sediments (de Lucas et al. 2014). Addition of *Tubifex* to accelerate oil sand tailings dewatering was first investigated by Yang et al. (2015; 2016), which showed that fluid fines tailings (FFT) with initial 4% solids content (S_c) by weight (i.e., 4 wt%) could reach 41 wt% S_c within 60 days in the presence of *Tubifex*, whereas the benchmark FFT could only reach 34% without *Tubifex*. *Tubifex* were able to survive in the environment of FFT (Yang et al. 2016). The increase in the consolidation rate was partly motivated by a matrix of *Tubifex* tunnels distributed within the solid matrix, increasing the permeability of the soil (de Lucas et al.

2016). The results from Yang et al. (2016) suggested that *Tubifex* might also work when the tailings became more compacted, hence motivating the subsequent phase of this work. The oil sands industry is faced with challenges to further dewater the MFT that has a higher S_c than the FFT. In general, MFT is defined as the tailings with S_c greater than 30 wt% and FFT has less than 30 wt% S_c. Nonetheless there is a lack of investigations in the feasibility of using *Tubifex* in the MFT, whereas MFT are more pervasive than FFT in the tailings ponds in Western Canada.

The present research was thus performed to investigate the effects of *Tubifex* on the consolidation of MFT. Moreover, the different composition of MFT when compared to FFT motivated the study of the survival of *Tubifex* in this type of tailings. In addition, the study also addresses whether *Tubifex* keeps improving dewatering over larger time scales than what studied so far. Finally, the potential of *Tubifex* to have an effect on the chemical composition of MFT, such as the content of cationic ions and anionic ions,was also investigated in this research. The specific objectives and the research methodology are therefore stated as follows: 1) *Tubifex* survival possibility in MFT at temperatures of 4°C and 20°C; 2) enhancement of the MFT dewatering process, using eleven settling column tests that lasted four months at varying *Tubifex* densities; 3) comparison of engineering properties (shear strength, pore water pressure distribution, density distribution, and chemical composition change) of MFT with and without *Tubifex* treatment; and 4) the long-term influence of *Tubifex* treatment on the dewatering of MFT using settling column tests that lasted thirteen months.

BACKGROUND OF TEST MATERIALS

Tubifex

The *Tubifex* worms used in the present research were in red color and 2 to 6 cm long as seen in Figure 1. *Tubifex* are indigenous in Alberta, Canada (Brinkhurst 1978; Whiting and Clifford 1983). They can survive in severely contaminated environment (Engle et al. 1994). Possibly *Tubifex* feeds on bacteria while bacteria feeds on organic matters in the tailings or slurries. Little oxygen is needed for *Tubifex* to inhabit in such an environment because of their high tolerance for reduced oxygen level (Chapman 2001). As a result, *Tubifex* density has been used as a bioindicator of pollution induced by heavy metals such as copper and lead (Lucan-Bouché et al. 1999). *Tubifex* were able to reduce the amount of sludge produced in biological wastewater treatment processes (Huang et al. 2007). *Tubifex* created the micro-tunnels in the sludge and separated the solids and the water more swiftly (Zhu et al. 2008). De Lucas (2014) observed that *Tubifex*-abundant beds had a higher permeability than defaunated beds.

MFT sample and conditioning

The MFT sample was originated from tailing pond sites in Canada in 2009, as the byproduct of oil sands extraction. The sample contains water, clay, silica, and a traceable amount of bitumen. This MFT was mixed into a homogeneous slurry in March 2014. This slurry of unknown initial S_c was stored and left undisturbed for the next two years. During storage, the self-weight consolidation and dewatering process started and the solids slowly separated from the water. In February 2016, the cap water released from the MFT sample was removed and the S_c of the sample was measured 47.9 wt%. For laboratory column tests in the present research, the MFT was diluted with cap water released from the tailings to reach the 30 wt% target. This is because 30 wt% is generally considered as the S_c boundary between MFT and FFT. The basic characteristics of the MFT are listed in Table 1. The organic content was estimated by drying samples using Vecstar Furnace for four hours at 500 °C.

The particle size distribution of the tailings is shown in Figure 2, measured with Mastersizer 2000 that can measure particles from 0.02 μm to 2,000 μm. In these tests, MFT was highly diluted with deionized water and mixed thoroughly. Figure 2 shows that 78% of the solids were finer than 44 μm. Thus the sands-to-fines ratio is estimated to be 0.28.

EXPERIMENTAL PROGRAM

A series of *Tubifex* survival tests in beakers were conducted at the air temperature of 20°C and 4°C without air pumping. This is a difference with the survival experiments in Yang (2016), where air was pumped into water column to improve mixing of water throughout the water column and oxygen availability. If successful, the possibility of not pumping air into the water column would constitute an important milestone for the technology. Settling column tests of MFT were conducted for a duration of about 4 months to investigate the influence of *Tubifex* on solid-water separation; the density of *Tubifex* was varied in the column tests. Lastly, the settling behavior of one column of MFT amended with *Tubifex* was recorded for thirteen months to investigate the long-term effect of *Tubifex*.

Tubifex survival rate in MFT

Yang et al. (2016) showed that *Tubifex* could survive in fluid fine tailings at the laboratory room temperature (20°C) without additional food supply when fresh air was pumped through a tube into the top released water to maintain water circulation and oxygen supply to the worms. To investigate the rate of *Tubifex* survival in MFT without air pumping, two batches of survival tests were conducted in a number of beakers for one month under following control conditions: 1) at the room temperature (20°C) without air pumping; and 2) at 4°C without air pumping. In the cold region of Alberta and given its long severe winter, it is critical to know whether *Tubifex* can survive under low temperature. The temperatures of 4°C and 20°C were selected based on what was possible at our laboratories. In addition, the low ambient temperature at 4 °C in the refrigerator is also near the temperature of tailings underneath the ice sheets in the cold season. Test results at the two temperatures can be later used as reference when understanding field applicability. Five batches of tests with fifteen beakers in each batch were performed and each batch was triplicated to observe the consistence of test results.

To prepare for the survival tests, beakers of 10 cm diameter were filled with 600 mL MFT specimen of 30 wt% initial S_c and eight *Tubifex* were added into each beaker. This resulted in a *Tubifex* density of 1018 individuals/m^2, which is comparable with the densities used by Yang (2016) in previous experiments. The beakers were stored at 20 °C or 4 °C without any additional food or air supply. The number of alive *Tubifex* in the MFT beakers was counted at 4, 7, 14, 21 and 28 days, respectively. At the end of survival tests, MFT specimens were diluted and rinsed through a sieve with opening diameter less than 1 mm, and the alive worms that remained on the sieve were counted.

Large-scale column tests

Three groups of settling column tests of *Tubifex*-treated tailings and two reference columns of non-treated tailings were established. Table 2 shows the configuration of all column tests. Different numbers of *Tubifex* were added into Group 7, 8 and 9 in order to investigate the effects of *Tubifex* density on the tailings dewatering process. Three *Tubifex* densities were adopted: 4200, 2000, and 1400 individuals/m^2. Then density of 1400 individuals/m^2 is typical in the field as noted by de Lucas (2014), which was also applied in the previous work (Yang et al. 2016). Note that the density of *Tubifex* is given in individuals/m2 for a consistency with natural sciences, and to match values observed in nature. In the natural environment *Tubifex* only dwell in the uppermost 10-15 cm of bed. The number of *Tubifex* added into each column in Table 2 was calculated from the column cross-sectional area and the field *Tubifex* concentrations. In columns C71, C72, and C73, *Tubifex* were added at the very beginning of the settling test, and then two more times at one and two months after the first addition. Every addition corresponds to a *Tubifex* density of 1400 individuals/m^2, leading to a total density of 4200 individuals/m^2. For columns in Group 8 and 9, there was only one addition at the beginning of the settling test. The rationale behind the differences in *Tubifex* addition events is to investigate the dewatering efficiency of these addition strategies. Two types of columns, i.e. Type 1 (0.55 m height and 10 cm inner diameter) and Type 2 (1 m height and 12 cm inner diameter), were used in the tests as shown in Figure 3. As a consequence, we established two reference columns C01 and C02 in each type of columns; the reference columns were filled with MFT not treated with *Tubifex*. Figure 3 shows the setup of the laboratory column tests.

The mudline settlement and pore water pressure were measured during the settling process. The mudline heights were captured periodically by an automated camera. Five piezometers were installed at the 11-cm height above the base in the columns as shown in Figure 3(a), and one piezometer was installed at the 19-cm height in the column C02. At these positions, portal holes of 1.0 cm diameter were drilled on the column walls (Merckelbach 1998a; 1998b) and piezometers were mounted. All other columns with *Tubifex* are shown in Figure 3(b). Piezometers were calibrated before use.

The original MFT of 47.9 wt% were diluted with water released from the tailings to reach the target S_c of 30 wt%. Diluted MFT was placed in the columns immediately after being thoroughly mixed. To compare the mudline height evolution, a constant initial height of 30 cm was set initially. The data logging system, including automatic recording camera and piezometers, was started immediately after the homogeneous MFT samples were filled into the columns. Numerous pictures were taken over the first hours and days of settling and consolidation process. However, given the low compaction rate of thick tailings, only one picture per day was required later in the process. Three days after the setup, there was 3 to 4 cm cap water released from MFT. Then fresh air was pumped through a tube into the top released water to maintain water circulation and oxygen supply to the worms (which was also conducted in Yang et al. 2016). Nevertheless, the outlet of the tube was placed at a distance above the mudline level to avoid the turbulence-induced erosion to the tailings.

Furthermore, 5-cm-high water was added on the top of the tailings mudline prior to the air pump, gently enough not to disturb the tailings settlement. All the water added into the tailings was the released water from the original tailings. The target numbers of *Tubifex* shown in Table 2 were placed on the mud bed surface of each column in Groups 7, 8, and 9.

At the end of settling tests, undrained shear strength (s_u) of tailings in each column was measured using Haake roto viscometer rv100 vane. The vane is 1.6 cm long and 2.2 cm wide, consisting of four equally angled, rectangular blades. The rate-controlled method of measurement was applied. Because of the limited height of tailings in the column and the size of vane, measurements were taken at just two depths in order to minimize the effects of disturbance on the s_u quality. One measurement was taken at 5 cm below the mudline surface and the other one 5 cm above the bottom of the column.

Long-term settling column

To investigate the long-term effect of *Tubifex* on the dewatering of MFT, one column (1 m height and 12 cm inner diameter) filled with 6 L MFT of 30.4 wt% S_c was established in May 2015. *Tubifex* were added into this column in three times on the 2nd, 16th, and 80th days, respectively, since the start of settling process. The long-term settling tests lasted for thirteen months until June 2016. The mudline height evolutions with time were recorded during the settling process, but not in an automatized manner as in the case of the other column tests.

Chemical compositions

The effects of *Tubifex* activities on the geochemistry of MFT and pore fluid was investigated by examining the chemical compositions of the test materials. Following samples were collected and examined for the chemical compositions: the original MFT samples without treatment, released water sample from the original MFT, and a sample at the end of settling tests. From the sediment sample, the pore water was extracted through a 5 cm Rhizon (a filter diameter of 0.15 μm). In total, 10 mL sample was obtained.

EXPERIMENTAL RESULTS

In this section, *Tubifex* contributions to tailings dewatering are evaluated by reporting the results from the measurements of the mudline settlement, S_c evolution, shear strength change, pore water dissipation and chemical composition change during the settling process. The results from the survival experiments are also reported here. Note that the *Tubifex* survival was tested over 30 days, the settling columns over a 112 days, and the long term column lasted 13 months.

Tubifex survival rate in MFT

Five batches of beaker tests were performed to explore the *Tubifex* survival rate in MFT. The *Tubifex* survival rates in MFT without air pumping under 20 °C are summarized in Table 3. The average survival rate of three beakers on the 28th day was 91.7 %, which was not lower than the result when the air was pumped into tailings (Yang et al. 2016). This investigation shows that the fresh air supply does not play a significant role in *Tubifex* survival in oil sands tailings being tested in the present research, which potentially made the application of the technique more practical.

The results of *Tubifex* survival at 4 °C in the refrigerator, which was also tested without air supply, are also shown in Table 3. The average survival rate of three beakers on the 28th day was 83.3%. The results imply that a higher temperature may moderately increase the survival rate of Tubifex. Figure 4 compares the average *Tubifex* survivals of triplicate beakers at three circumstances, two tested in the present study, and a final one from Yang (2016). It is shown that extra air supply and water circulation did not improve the *Tubifex* survival rate in oil sands tailings under 20 °C and *Tubifex* were able to live at 4 °C in the cold region.

Note that, apart from temperature, other important factors such as the presence of sustenance (e.g. bacteria) may also be relevant to the survival of *Tubifex*, but beyond the scope of this research. The present results should be seen as an indication of how *Tubifex* can perform under the sustenance already present in tailings, but without further considerations over the effect of sustenance of *Tubifex* survival and its availabilty in oil sand tailings.

Settling column tests

The initial height of MFT in the columns was not exactly 30 cm, due to the uncertainties during column test preparation. Therefore the mudline height was normalized using Equation 1:

$$h = h_s(H/h_{s0}) \tag{1}$$

where H (= 30.8 cm) is the greatest initial mudline height of all settling columns, h_{s0} is the initial height of each column, h_s is the time-dependent measured height, and h (in cm) is the normalized height.

The h versus time evolutions of selected tests are shown in Figure 5. It is observed that tailings treated with *Tubifex*, represented by solid lines, reached a lower mudline height than the reference columns without any *Tubifex* treatment, represented by the dotted lines. This confirms that *Tubifex* treatment led to a more compacted sediment than non-treated tailings during the same time period and *Tubifex* were capable of accelerating the dewatering process of MFT.

The final mudline height in each column was recorded and the average value of Groups 7, 8 and 9 was summarized in Table 4. The average final height of reference columns C01 and C02 was 19.8 cm, whereas the average final height of tailings treated with increasing *Tubifex* densities were 18.5, 18.1 and 17 cm, respectively. It shows that more worms resulted in more compacted tailings. Generally, the final mudline height of non-treated tailings was 4 to 16.5% higher compared to that of *Tubifex*-treated tailings in nine columns. As shown in Figure 6, the average final heights of non-treated tailings were 7%, 9.4%, and 16.5% higher than that of tailings treated with 1400, 2000 and 4200 individuals/m^2 *Tubifex* respectively. The differences between the average final heights treated with different *Tubifex* densities is attributed partly to differences in column diameter. Thus we can only conclude that *Tubifex* had a positive effect in tailings dewatering, achieving a lower final equilibrium height, but the effect of density was only revealed in the initial consolidation rate, but not clearly in the final equilibrium height.

The solids content (S_c, in percentage of total mass) of the dewatered MFT was calculated based on the measured mudline height (h_s) and specific gravity (G_s) of tailings, using Equation 2:

$$S_c = \frac{m_s}{m_s + \rho_w\left(\pi r^2 h_s - \frac{m_s}{G_s \rho_w}\right)} \qquad (2)$$

where m_s is the mass of solids and ρ_w is the density of water, and r is the radius of the testing column. Figure 7 shows a schematic of the MFT sediment separated from the released water. The S_c evolutions with time of tests C71, C72 and C73 are shown in Figure 8. After 112-day settlement, the final S_c of *Tubifex* treated tailings reached 47.1 wt %, 48.1 wt %, and 48.2 wt %, respectively, whereas the final S_c of non-treated C01 reached only 43.2%. Comparing the maximum S_c reached by *Tubifex* treated tailings with that of non-treated tailings reveals that the *Tubifex* treated tailings exhibit an increase in S_c 30% larger than when not treated. Also it was noted that S_c of MFT specimen only reached 47.9 wt % under two years of self-weight consolidation. Assuming an initial S_c of 30% in the MFT specimen (which is a safe assumption since 30% is usually the S_c in fresh MFT drums as provided by the industry), and given the similar initial tailings thickness, it can be concluded that *Tubifex* treated tailings can reach S_c typical of years of consolidation in only 3 to 4 months, for this particular type of tailings. Clearly, *Tubifex* played a significant role in facilitating MFT dewatering rate.

Equation 2 is used to estimate the average S_c of the MFT sediment, assuming that the sediment solids are homogeneously distributed. However, the sediment distribution may be heterogeneous due to the segregation throughout the settling process. At the end of settling tests, two samples were taken from the sediment bed at 5 cm and 15 cm above the bottom of the cylinder and the solids contents were measured. Figure 9 shows the measured S_c versus the height above the column base. It is shown that S_c was not homogeneously distributed with the height; S_c of deeper section is approximately 2 to 5 percentage points greater than S_c of the upper section.

Undrained shear strength

The distribution of s_u values as a function of *Tubifex* density and depth in the tailings are shown in Figure 10. In general, the tailings strength was low since it had about 120% water content. However, the strength increased with the *Tubifex* treatment, particularly for the strength near the bottom of the columns, as shown in Figure 10. The tailings at the end of tests were no longer homogeneous due to sediment segregation, as also confirmed by the S_c distribution. The strength of the bottom samples was greater than that near the surface. The lower s_u near the mud-water surface was caused by the low solids content and finer particles. The average strength of three columns treated with the same *Tubifex* density (1400, 2000, and 4200 individuals/m^2) located in the bottom were 115 Pa, 148 Pa, and 150 Pa respectively. However, the average strength of two non-treated tailings was only 90 Pa. The value of s_u of tailings treated with 4200 individuals/m^2 *Tubifex* was 66.7% greater than s_u of the non-treated MFT. In addition, it is noticed that s_u increased with the density of *Tubifex* treatment. The shear strength of the tailings increases with the increase of solid content. As observed in this research, addition of the *Tubifex* accelerated the dewatering process of MFT. Thus the more *Tubifex* added, the solid content of tailings grows faster. The largest studied S_c distributions were shown by two particular *Tubifex* samples, one at 2000 individuals/m^2 and another one at 4200 individuals/m^2. For these, the near bottom S_c was approximately 200 Pa, and the near surface S_c was larger than 100 Pa.

Figure 11 shows the correlation of measured s_u versus measured S_c at two depths within the final beds. The correlation between s_u and S_c is not clear. We attribute this lack of correlation to the very low strength exhibited by surficial layers in tailings, which our measuring instrument may not be able to detect as accurately as for greater strengths.

Pore water pressure

Figure 12 shows the water pressure records throughout the settling tests. Two records of the pore water pressure sensors were plotted because the other four showed evidence of malfunctioning during several episodes. Note that the piezometers used for this work measured total pressure, therefore recording changes in atmospheric pressure (the data is corrected for this) and in the overlying water. In general, during the first five days pore water pressure of both columns dropped because the settlement commenced as stated by Miller (2016). Three to four centimeter cap water released from MFT was noticed three days after the tests got started. Then 5-cm-high water was added on the top of the tailings gently. Consequently, the pore water pressure of the *Tubifex* treated samples started to increase gradually. However, the pressure reached the values that are not understood. We attribute this abnormal behavior to the *Tubifex* worms tunneling at or around the pore water pressure sensors. The pore water pressure of non-treated tailings was almost constant during the whole period. Slowly decreasing towards the end of the tests. The first addition of *Tubifex* took place on the seventh day after tests started. At 20 days, the pore water pressure of *Tubifex* treated tailings started dissipating faster than non-treated tailings. This is in good agreement with lower mud-water interface and higher s_u of tailings with *Tubifex* than tailings without treatment. The enhanced pore water pressure dissipation should be attributed to the channels created by *Tubifex* movement in the tailings. The water trapped in fine tailing particles released through these tunnels which increased the tailings hydraulic permeability (de Lucas et al. 2016).

Chemical composition

In total, 10 mL sample was obtained for each of the tests of chemical compositions. The major anion and cation macro ion concentrations in the samples were analyzed, which were undiluted, diluted 10 times, and diluted 100 times with Ion Chromatography respectively. The concentrations are shown in Figure 13 and Figure 14.

In Figure 13, the tailings sample and the water sample had the similar amount of cationic ion concentrations. *Tubifex* did not make any significant change on the cationic ion concentration. The anionic ion concentration showed the same pattern except for the sulfate in Figure 14. The sulfate content of cap water sample released from the original MFT was much lower than that of tailings, which was because the sulfate was attached to solid particle surface instead of being suspended in the cap water. Furthermore, a significant decrease in sulfate was shown in *Tubifex* treated tailings, which might be caused by the presence of *Tubifex* facilitating the development of sulfate-reducing bacteria in MFT.

Khangarot (1991) suggested that Os and Ag were the most toxic and Na and K were the least toxic ions in tailings. In general, Ag, Hg, Cu and Cd are more toxic than Na, K and Mg. Jones (1938) observed that an exposure of Cu and Pb at 1000 mg/L would kill *Tubifex* in several hours. Brokovic-Popovic and Popovic (1977) determined that the 48h LC50 (Median-lethal concentration: the concentration of the chemical that kills 50% of the test animals during the observation period) values in mg/L were: Cu, 0.006-0.89; Zn, 0.11-60.2; Cr, 0.06-4.57; Ni, 0.08-61.4; Cd, 0.03-0.72; and Hg, 0.06-0.1. Whitley (1967) found the LC50 values of 49.0 mg/L for Pb and 46 mg/L for Zn, and also proved that the toxic action is owing to the formation of mucus metal complex that precipitates on the body wall of worms and blocks the exchange of O_2 and CO_2. As shown in Figure 13, the tailings specimen in the present research did not contain the most toxic metals such as Os, Ag, Hg, Cu, Cd, Pb, Gr, Zn or Ni. On the other hand, the amount of these toxic metals are below the detection limit. However, the tailings contained more Na than any other metals, which is one the least toxic metals for *Tubifex*. As a result, the oil sands tailings seemed to offer a safe environment for *Tubifex* with respect to metallic ions. This may be one of the reasons for which the survival rate of *Tubifex* appeared to be promising in MFT.

Long-term settling column

Yang et al. (2016) showed that *Tubifex* can "dig" into the tailings sediments as deep as 42 cm. In the present research, the same column CL was used to examine the *Tubifex* enhancement on the dense tailings dewatering in a duration of 13 months. Figure 15 shows the time evolutions of the mudline height and solids content. The tailings in the column treated with *Tubifex* increased to 51.3 wt % from 30.4 wt % after 13 months of dewatering. The channels made by *Tubifex* movement were clearly visible in the thick tailings, as shown in Figure 16. For comparison, the same sample was mixed on March 5, 2015, at an initial S_c of 34 wt %, and the sample started to consolidate without any *Tubifex* treatment. After eleven months of settling, the released water was removed and S_c of tailings below was measured 44 wt % in February 2016, which indicated 29.4% increase in S_c. In summary, *Tubifex*-accelerated tailings reached 50.9 wt % from 30.4 wt % within nine months, resulting in an increase of 67.4% in $S_{c,}$ which shows a 129% higher S_c increase within a shorter time period than that of the non-treated tailings. The long-term test results confirmed that *Tubifex* also worked well for the thick tailings in the long term without continuously addition of *Tubifex*. However we lack of evidence to confirm how much *Tubifex* was alive over the 13 months, and the weak declining population trend observed for the survival tests for one month is likely resulting in a less active and less healthy *Tubifex* community over time. We hypothesize that finding optimal conditions for *Tubifex* to grow and reproduce would very much improve the already positive results displayed by this 13 months experiment.

CONCLUSIONS

A series of beaker experiment and large-column tests were carried to study the survival rate of *Tubifex* and the effect of *Tubifex* on dewatering and strengthening of MFT. Time histories of mud line heights and, S_c, and measurements of S_u were selected as indicators of the efficiency of the treatment method. The following conclusions may be drawn.

1. The average survival rate at 20 °C and 4 °C on the 28th day remained in the 80 to 90% range. The water re-circulation did not contribute to *Tubifex* survival rate in oil sands tailings at 20 °C and *Tubifex* showed comparable survival rate at 4 °C ambient temperature.
2. *Tubifex* enhanced the dewatering process of MFT of 30 wt % initial S_c. Increasing *Tubifex* densities resulted in almost equally compacted tailings with equivalent S_c and s_u. Tailings treated with density of 4200 individuals/m^2 could reach 48.2 wt% S_c after three months of settlement, which is 11.6 % more compacted than non-treated tailings. Comparing the maximum S_c reached by *Tubfiex* treated tailings with that of non-treated tailings reveals that the *Tubifex* treated tailings exhibit an increase in S_c 30% larger than when not treated. The increase in S_c exhibited for *Tubifex* treated tailings over 3 to 4 months is equivalent to the increase in S_c over 2 years for non-treated tailings.
3. *Tubifex* activities accelerated the pore water pressure dissipation through the channels made by worm's movements.
4. *Tubifex* barely affected the tailings cationic and anionic ion composition except for the sulfate. The most toxic ions to *Tubifex* was not present in the tailings in this study. As one of the least toxic ions, Na is the dominant metallic ion in tailings; however, *Tubifex* was able to survive in such concentration of cations and anions.
5. *Tubifex* showed potentials to facilitate tailings dewatering in the long term, and despite the likely decaying population. Tailings treated with *Tubifex* could reach 50.9 wt % S_c within nine months, which was the maximum duration the tests in this research. The

increase S_c 67.4 wt % was 129% greater than S_c increase 29.4% of non-treated tailings after eleven-month dewatering.

ACKNOWLEDGEMENT

This work was supported by China Postdoctoral Science Foundation Grant (No. 2018M630647). The first author is also grateful to the China Scholarship Council (No. CSC [2014] 7407) for funding the studies at the University of Alberta and Deltares.

REFERENCES

Alberta Energy. 2014. Alberta's oil sands: the facts. Government of Alberta, Edmonton, AB.

BGC Engineering Inc. 2010. Oil sands tailings technology review. Oil Sands Research and Information Network report TR-1, School of Energy and the Environment, University of Alberta, Edmonton, AB.

Brigmon, R. L., Berry, C. J., Wade, A., and Simpson, W. 2016. Bioprocessing-based approach for bitumen/water/fines separation and hydrocarbon recovery from oil sands tailings. Soil and Sediment Contamination: An International Journal, 25(3): 241-255. doi:10.1080/15320383.2015.1020408.

Brinkhurst, R.O. 1978. Freshwater oligochaeta in Canada. Canadian Journal of Zoology, 56(10): 2166–2175. doi: 10.1139/z78-292.

Brokovic-Popovic, I., and Popovic, M. 1977. Effects of heavy metals on survival and respiration rate of tubificid worms: Part I-Effects on survival. Environmental Pollution, 13(1): 65-72. doi: 10.1016/0013-9327(77)90034-9.

Chapman P.M. 2001. Utility and relevance of aquatic oligochaetes in Ecological Risk Assessment. *In* Rodriguez P., Verdonschot P.F.M. (eds) Aquatic Oligochaete Biology VIII. Developments in Hydrobiology, Springer, Dordrecht, pp. 149-169. https://link.springer.com/chapter/10.1007/978-94-010-0597-5_17.

de Lucas Pardo, M.A. 2014. Effect of biota on fine sediment transport processes: a study of Lake Markermeer. PhD thesis, Department of Environmental Fluid Mechanics, Delft University of Technology, Delft, the Netherlands.

de Lucas Pardo, M.A., Yang, X., Ibanez, M., Sittoni, L., Deng, L., and Ulrich, A. 2016. Tubifex: a biological method for enhancing dewatering of oil sands tailings. *In* Proceedings of the 6th International Oil Sands Tailings Conference, Lake Louise, AB, pp. 1-6.

Energy Resources Conservation Board. 2009. Directive 074 – Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes, Calgary, AB.

Engle, V.D., Summers, J.K., and Gaston, G.R. 1994. A benthic index of environmental condition of Gulf of Mexico estuaries. Estuaries, 17(2): 372–384. doi: 10.2307/1352670.

Entezari, I., Rivard, B., Lipsett, M.G., and Wilson, G.W. 2016. Prediction of water content and normalized evaporation from oil sands soft tailings surface using hyperspectral observations. Canadian Geotechnical Journal, 53(10): 1742-1750. doi: 10.1139/cgj-2015-0416.

Herman, D.C., Fedorak, P.M., and Costerton, J.W. 1993. Biodegradation of cycloalkane carboxylic acids in oil sands tailings. Canadian Journal of Microbiology, 139(6): 576-

580. doi: 10.1139/m93-083.

Huang, X., Liang, P., and Qian Y. 2007. Excess sludge reduction induced by Tubifex Tubifex in a recycled sludge reactor. Journal of Biotechnology, 127(3): 443–451. doi:10.1016/j.jbiotec.2006.07.035.

Jeeravipoolvarn, S. 2010. Geotechnical behavior of in-line thickened oil sands tailings. PhD thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB.

Jones, J.R.E. 1938. Antagonism between two heavy metals in their toxic action on freshwater animals. Proceedings of the Zoological Society of London, A108 (4): 481-499. doi: 10.1111/j.1096-3642.1939.tb00036.x.

Khangarot, B.S. 1991. Toxicity of metals to a freshwater tubificid worm, Tubifex t ubifex (Muller). Bulletin of Environmental Contamination and Toxicology, 46(6): 906-912. doi: 10.1007/BF01689737.

Liang, J., Guo, Z., Deng, L., and Liu, Y. 2015. MFT consolidation through microbial induced calcium carbonate precipitation. Canadian Journal of Civil Engineering, 42(11): 975–978. doi: 10.1139/cjce-2015-0069.

Lucan-Bouché, M.L., Biagianti-Risbourg, S., Arsac, F., and Vernet, G. 1999. An original decontamination process developed by the aquatic oligochaete Tubifex tubifex exposed to copper and lead. Aquatic Toxicology, 45(1): 9–17. doi: 10.1016/S0166-445X(98)00091-5.

Merckelbach, L.M. 1998a. Report 1-98 Laboratory experiments on consolidation and strength evolution of mud layers, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands.

Merckelbach, L.M. 1998b. Report 7-98 Consolidation and strength evolution of Caland-Beer Channel mud measurement report on laboratory experiments. Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands.

Miller, W.G., Scott, J.D., and Sego, D.C. 2016. Influence of extraction process and coagulant addition on Thixotropic strength of oil sands fine tailings. Canadian Institute of Mining, Metallurgy and Petroleum Journal, 1(3): 197-205. https://www.osti.gov/etdeweb/biblio/21392950

Mulligan, C.N., and Roshtkhari, S.J. 2016. Application of microbial culture and rhamnolipid for improving the sedimentation of oil sand tailings. Journal of Bioremediation & Biodegradation, 7(4): doi:10.4172/2155-6199.1000358.

Powter, C.B., Biggar, K.W., Silva, M.J., McKenna, G.T., and Scordo, E.B. 2011. Review of oil sands tailings technology options. *In* Proceedings of 14th International Conference on Tailings and Mine Waste, Fort Collins, CO. pp. 381-391.

Siddeque, T., Kuznetsov, P., Kuznetsova, A., Arkell, N., Young, R., Li, C., Guigard, S., Underwood, E., and Foght, J.M. 2014a. Microbially-accelerated consolidation of oil sands tailings. Pathway I: changes in pore water chemistry. Frontiers in Microbiology, 5(106): 1-15. doi: 10.3389/fmicb.2014.00106.

Siddeque, T., Kuznetsov, P., Kuznetsova, A., Li, C., Young, R., Arocena, J.M., and Foght, J.M. 2014b. Microbially-accelerated consolidation of oil sands tailings. Pathway II: solid phase biogeochemistry. Frontiers in Microbiology, 5(107): 1-15. doi: 10.3389/fmicb.2014.00107.

Wang, C., Han, C., Lin, Z., Masliyah, J., Liu, Q., and Xu, Z. 2016. Role of preconditioning cationic zetag flocculant in enhancing mature fine tailings flocculation. Energy Fuels, 30(7): 5223-5231. doi:10.1021/acs.energyfuels.6b00108.

Whitley, L.S. 1967. The resistance of tubificid worms to three common pollutants. Hydrobiologia, 32(1): 193-205. doi: 10.1007/BF00179550.

Whiting, E.R., and Clifford, H.F. 1983. Invertebrates and urban runoff in a small northern stream, Edmonton, Alberta, Canada. Hydrobiologia, 102(1): 73–80. doi: 10.1007/BF00006052.

Wolfaardy, G.M., Hendry, M.J., and Korber, D.R. 2008. Microbial distribution and diversity in saturated, high pH, uranium mine tailings, Saskatchewan, Canada. Canadian Journal of Microbiology, 54(11): 932-940. doi: 10.1139/W08-084.

Yang, X., de Lucas Pardo, M.A., Deng, L., Sittoni, L., Ulrich, A., and Chen, Q. 2015. Tubifex: A biological method for dewatering oil sands tailings. *In* Proceedings of Tailings and Mine Waste 2015, Vancouver, BC. pp. 499-507.

Yang, X., de Lucas Pardo, M.A., Ibanez, M., Deng, L., Sittoni, L., Ulrich, A., and Chen, Q. 2016. Addition of Tubifex accelerates dewatering of oil sands tailings. Canadian Journal of Civil Engineering, 43(12): 1025-1033. doi:10.1139/cjce-2016-0308.

Zhu, H., Wei, Y., and Wang, Y. 2008. Effect of Tubificidae on activated sludge settling performance. Acta Scientiae Circumstantiae, 28(5): 910-915.

https://caod.oriprobe.com/articles/14042918/Effect_of_Tubificidae_on_activated_sludge_settling.htm.

List of Figures

Table 1. Properties of MFT samples

Property	Value
Bulk density (g/cm^3)	1.34
Solids content (wt%)	47.9
G_s of solids	2.20
Plastic limit	28
Liquid limit	48
Plasticity Index	20
Organic content (wt%)	21.2

Table 2. Configuration of large-scale column tests

Group	Column ID	Initial S_c (wt %)	No. of *Tubifex*	Tubifex Density (individuals/m^2)	Size [2]	Piezometer used
G7	C71	30	48	4200 [1]	Large	Y
	C72	30	48	4200 [1]	Small	N
	C73	30	48	4200 [1]	Small	N
G8	C81	30	16	1400	Large	Y
	C82	30	16	1400	Large	N
	C83	30	16	1400	Large	N
G9	C91	30	23	2000	Large	Y
	C92	30	23	2000	Large	N
	C93	30	23	2000	Small	N
G10	CL[3]	30	48	4200 [1]	Large	N
R1	C01	30	0	0	Small	Y
R2	C02	30	0	0	Large	Y

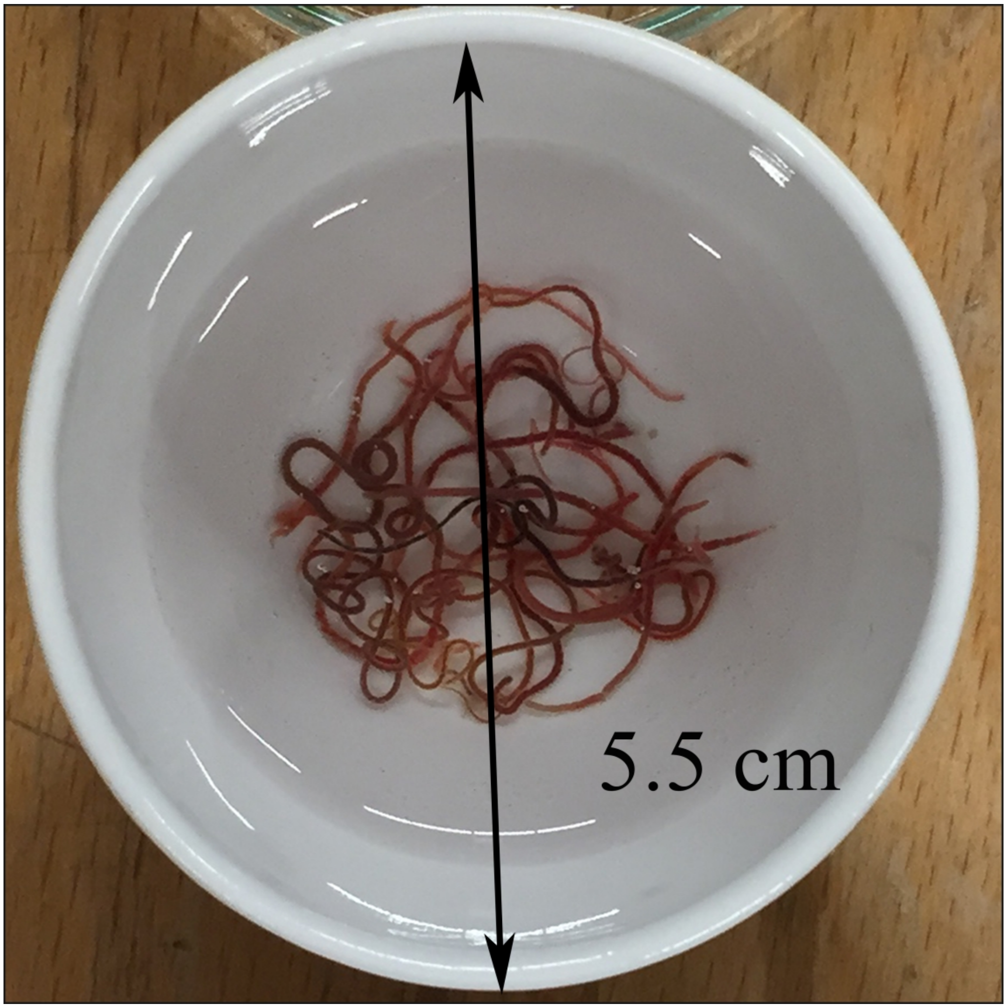
Note: 1. Tubifex were added at the beginning, 1 month, and 2 months at 1400 individuals/m^2 each time, leading to a total density of 4200 individuals/m^2. 2. Small column dimension: 10 cm inner diameter and 0.55 m height, and large column dimension: 12 cm inner diameter and 1 m height. 3. CL is the long-term settling column that lasted in the laboratory for 13 months; however, the total number and density of Tubifex may not be accurate.

Table 3. Tubifex survival rate without air pumping

Days of measurement	20 °C			4 °C		
	Beaker 1	Beaker 2	Beaker 3	Beaker 1	Beaker 2	Beaker 3
0	8	8	8	8	8	8
4	7	6	4	9	9	9
7	6	3	6	8	7	9
14	6	6	7	9	8	9
21	6	8	6	8	8	8
28	9	7	6	8	7	5

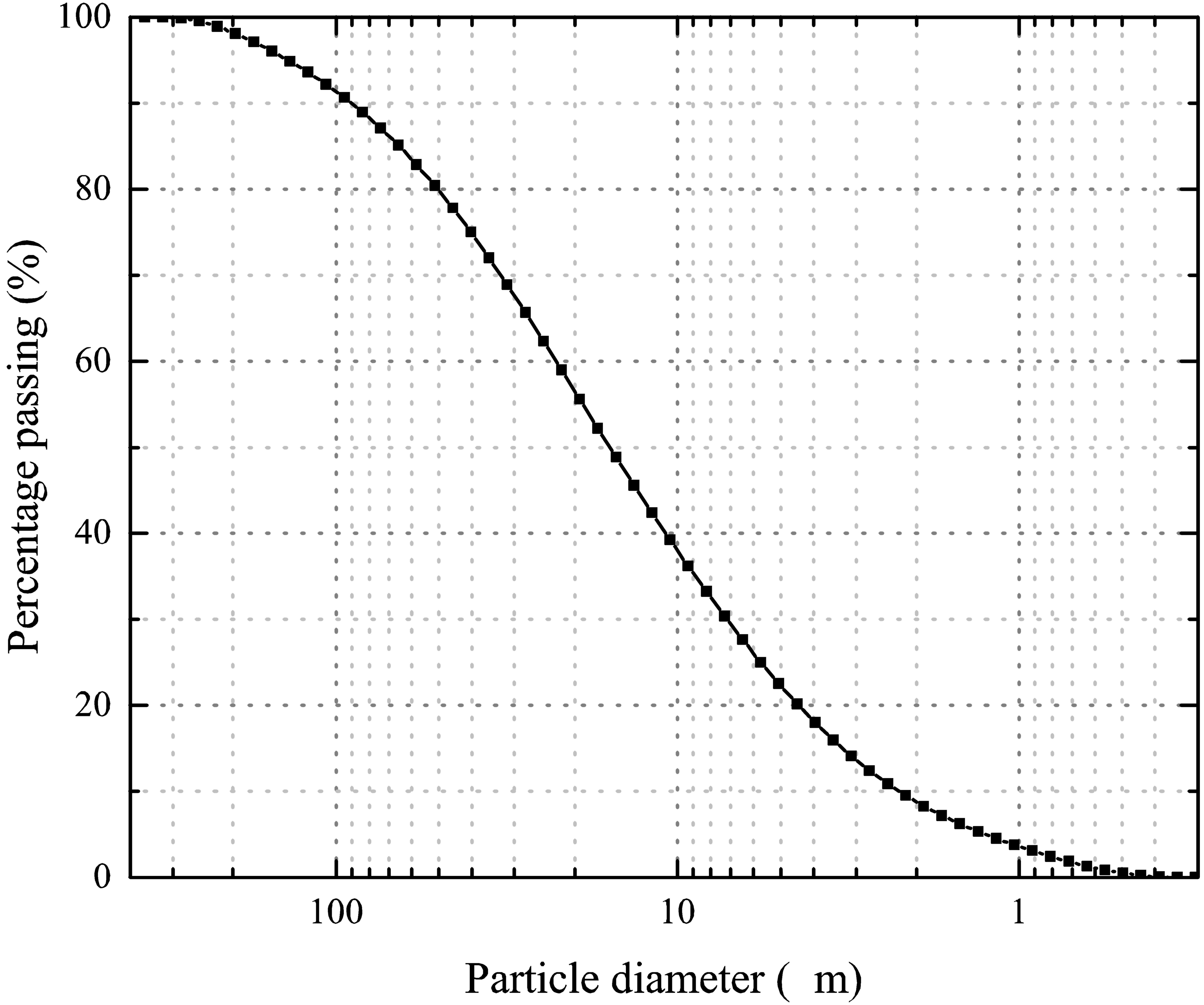
Table 4. Final mudline heights and the average of each group treated with various densities

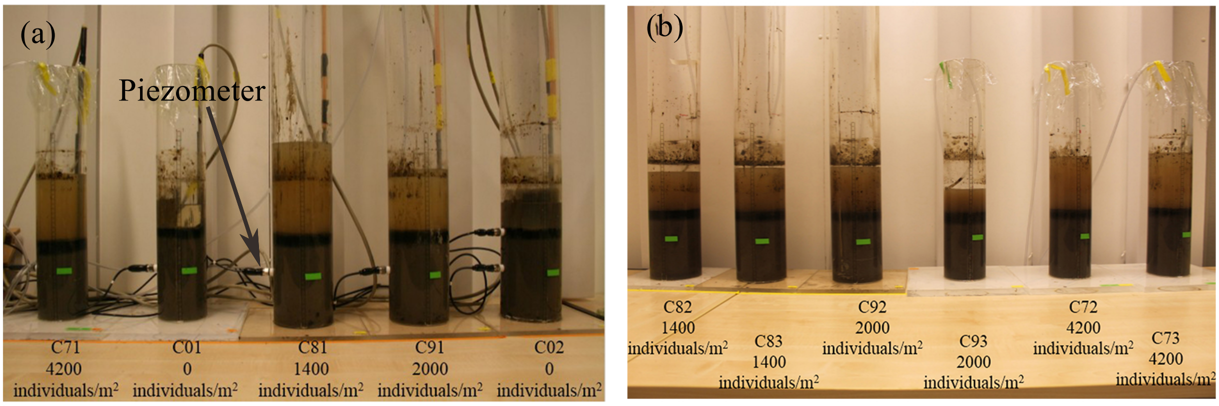
Tubifex density (individuals/m^2)		0	1400	2000	4200
Mudline height, h_s (cm)	Column 1	19.6	19.3	19.1	17.4
	Column 2	20.0	18.4	16.9	16.9
	Column 3	n/a	17.9	18.2	16.8
	Average	19.8	18.5	18.1	17.0

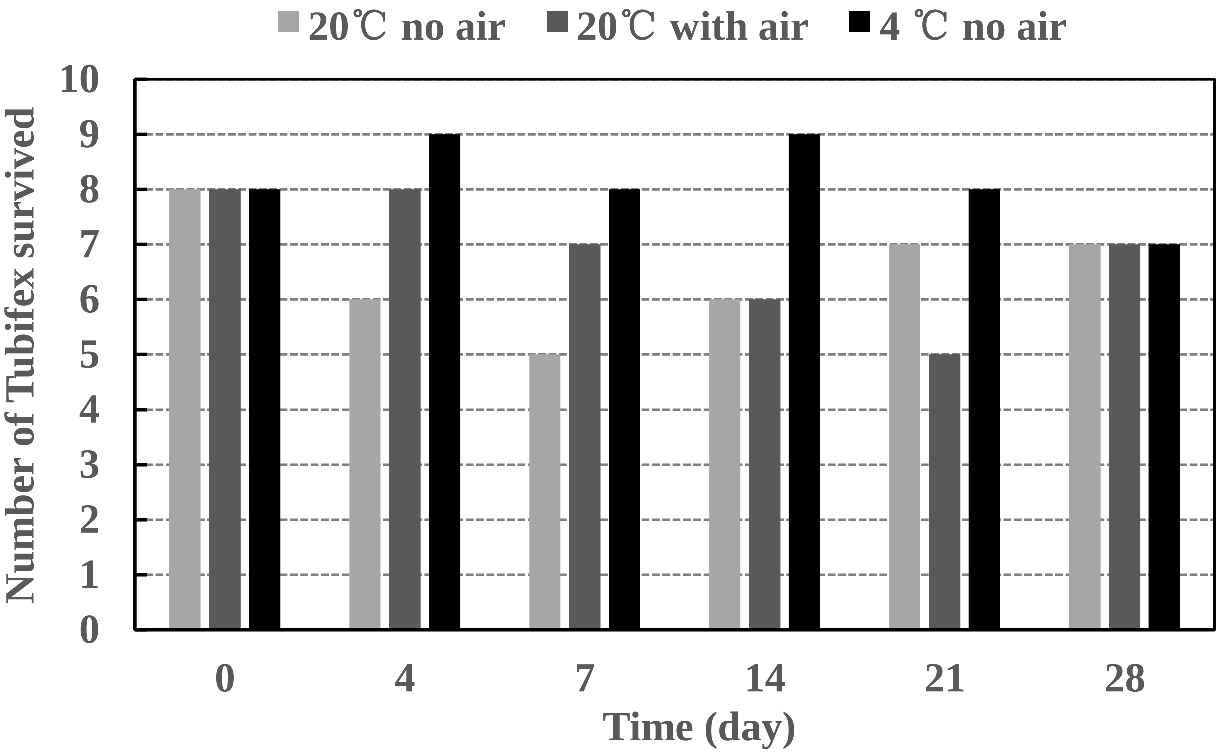


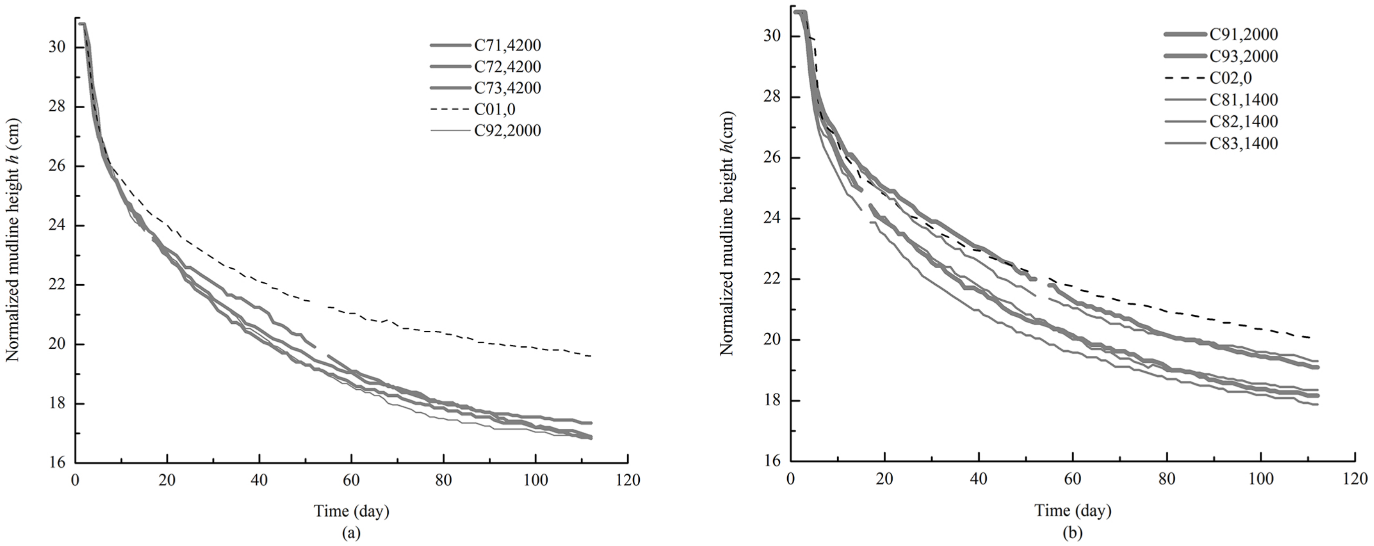
Tubifex applied in the current experiments

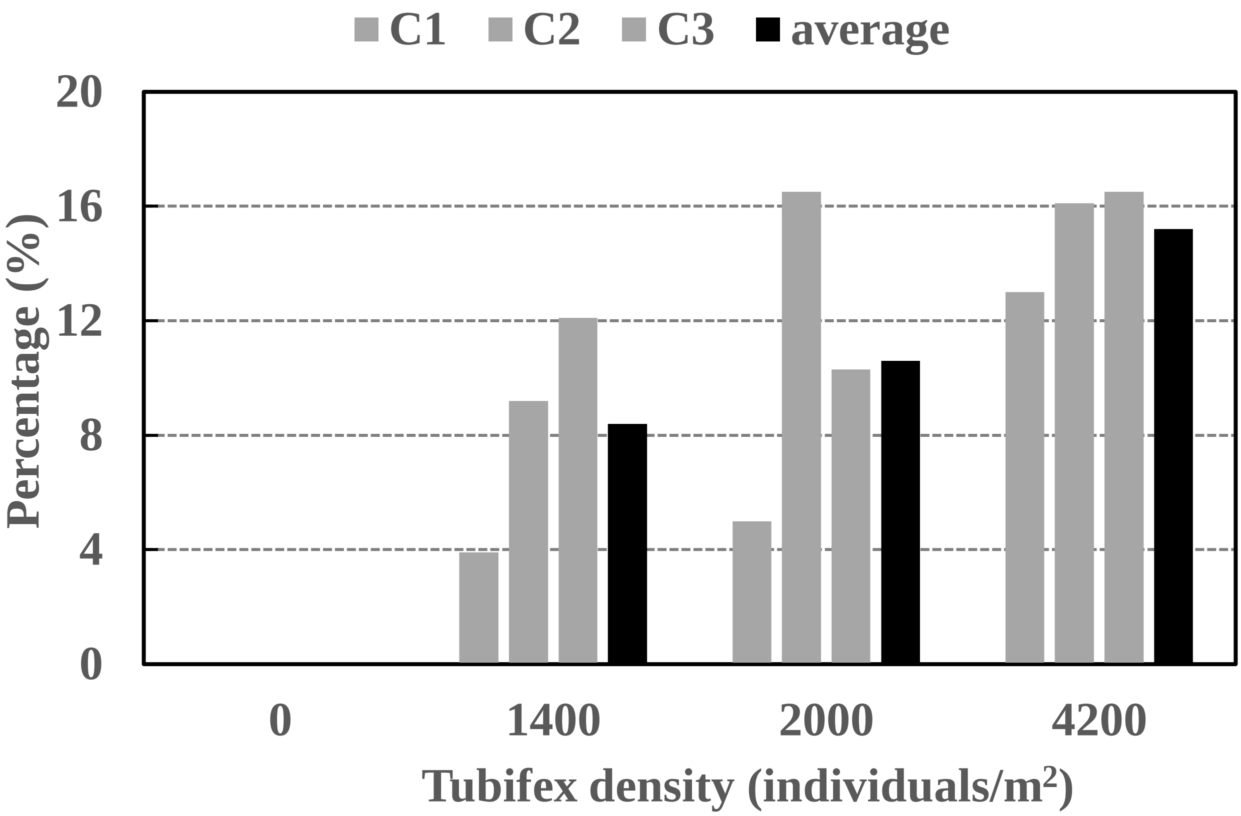
321x321mm (300 x 300 DPI)

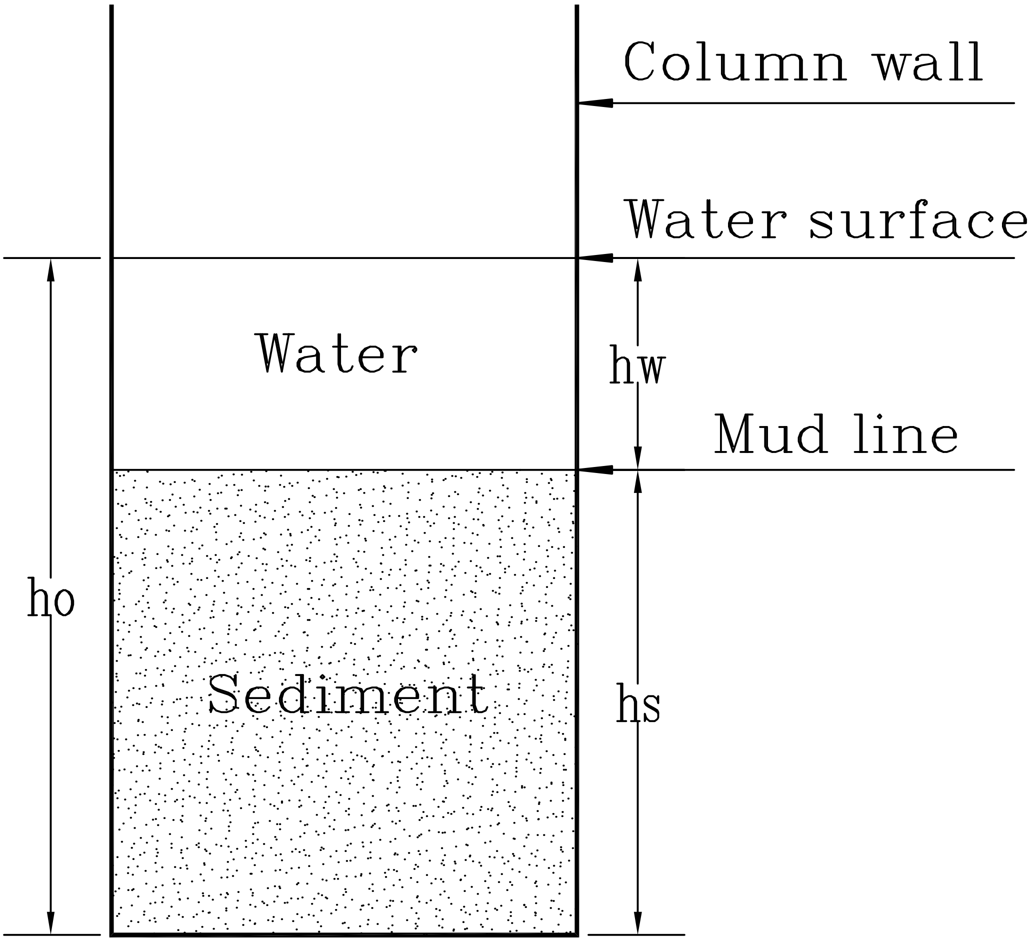

Percentage passing (%)
100
80
60
40
20
0
100
10
1
Particle diameter (m)

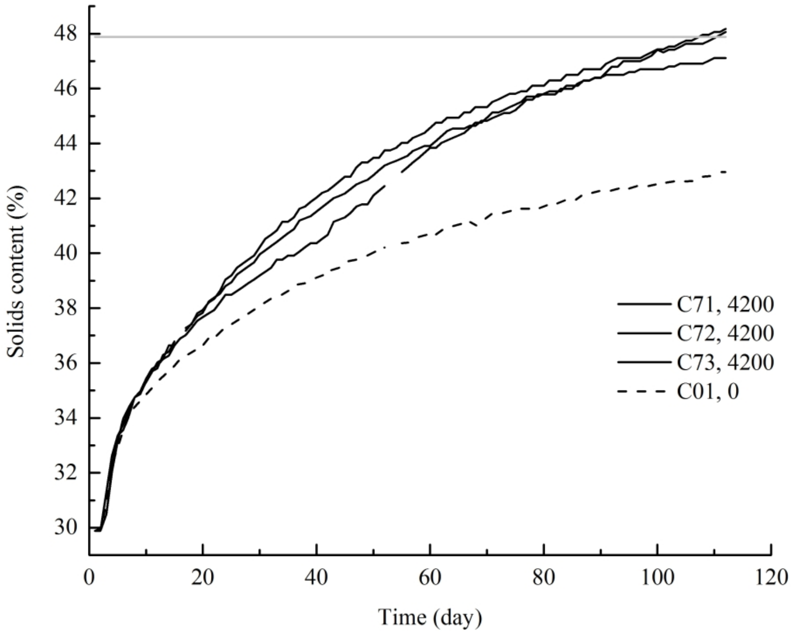

(a)
Piezometer
C71
4200
individuals/m^2
C01
0
individuals/m^2
C81
1400
individuals/m^2
C91
2000
individuals/m^2
C02
0
individuals/m^2
(b)
C82
1400
individuals/m^2
C83
1400
individuals/m^2
C92
2000
individuals/m^2
C93
2000
individuals/m^2
C72
4200
individuals/m^2
C73
4200
individuals/m^2


20℃ no air
20℃ with air
4 ℃ no air
Number of Tubifex survived
0
1
2
3
4
5
6
7
8
9
10
0
4
7
14
21
28
Time (day)


Normalized mudline height h (cm)
C71,4200
C72,4200
C73,4200
C01,0
C92,2000
Time (day)
(a)
Normalized mudline height h(cm)
C91,2000
C93,2000
C02,0
C81,1400
C82,1400
C83,1400
Time (day)
(b)

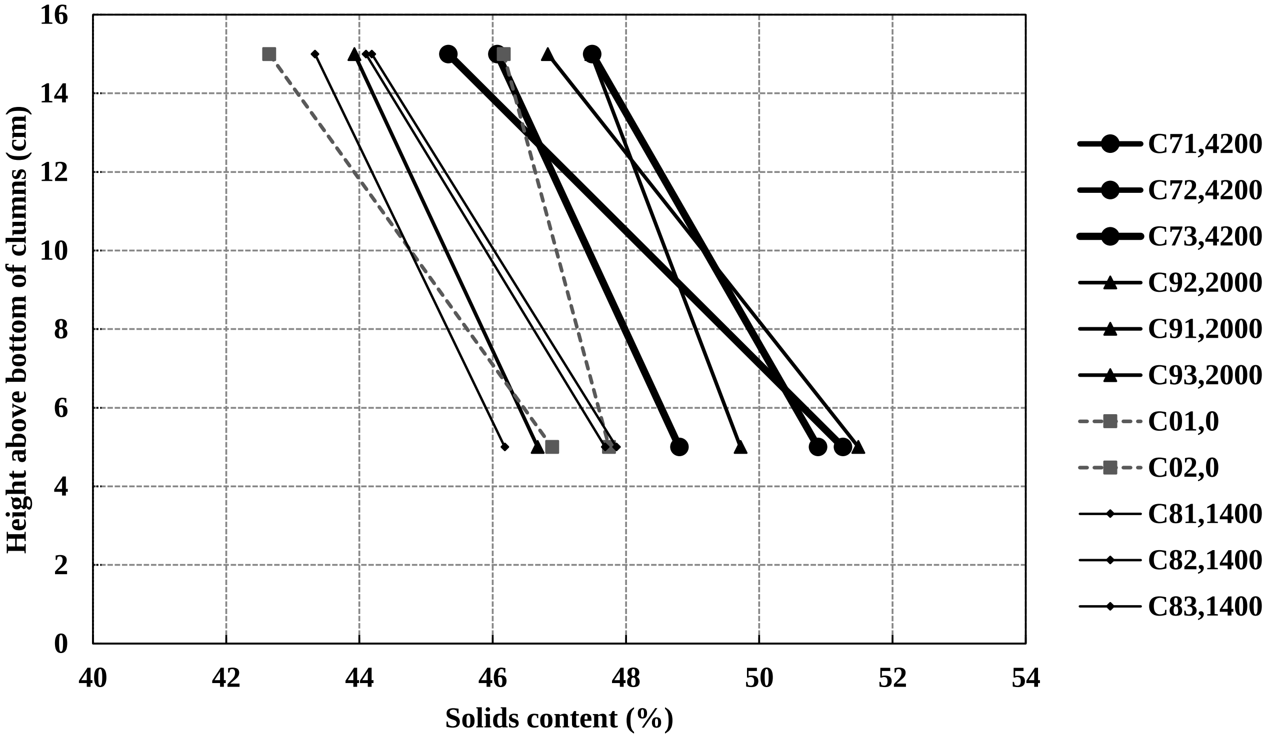

C1
C2
C3
average
20
16
12
8
4
0
Percentage (%)
0
1400
2000
4200
Tubifex density (individuals/m²)

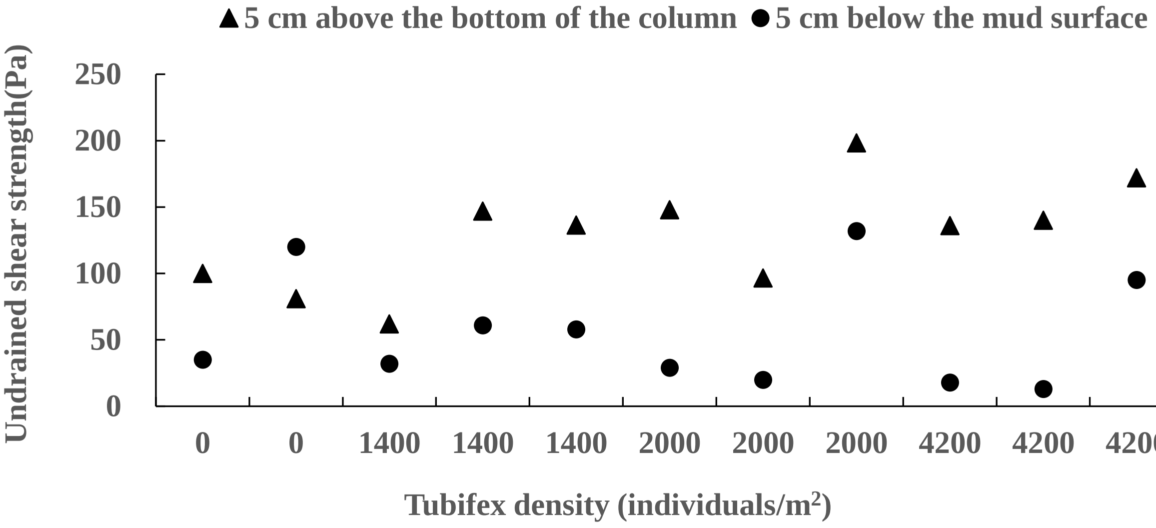

Column wall
Water surface
Water
hw
Mud line
ho
Sediment
hs

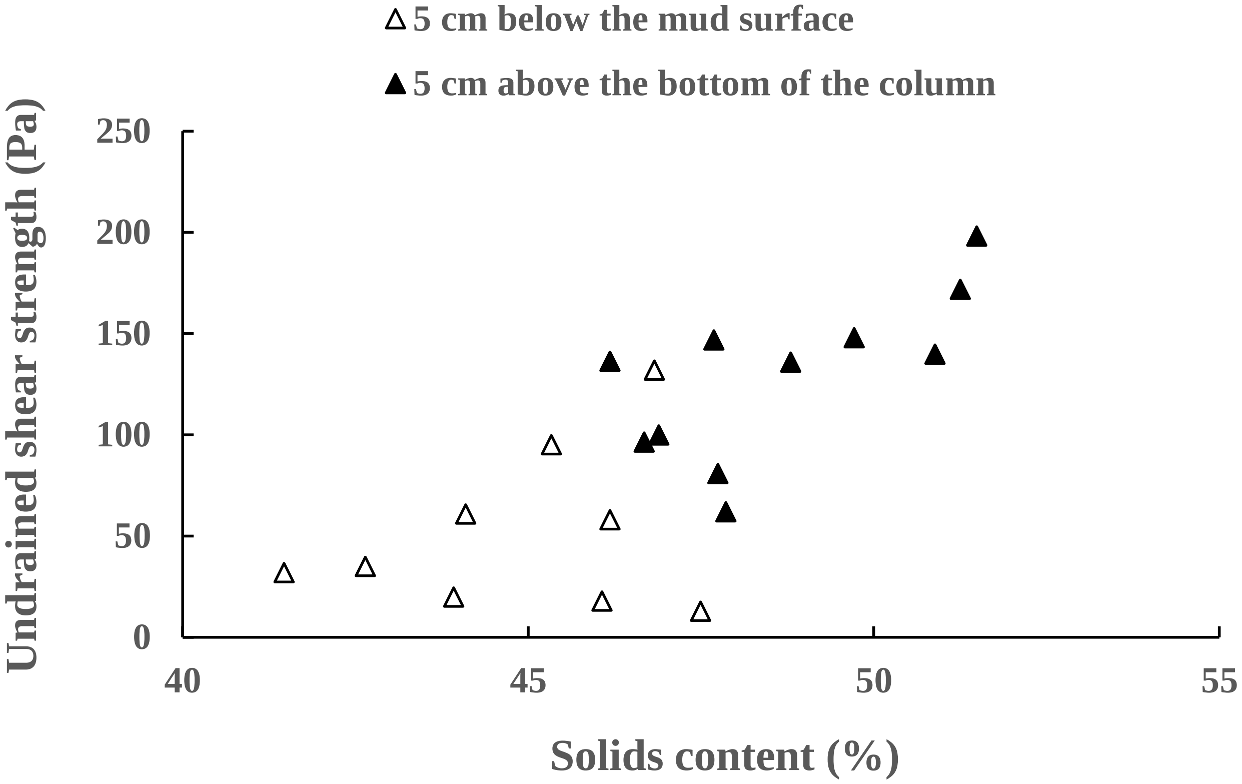


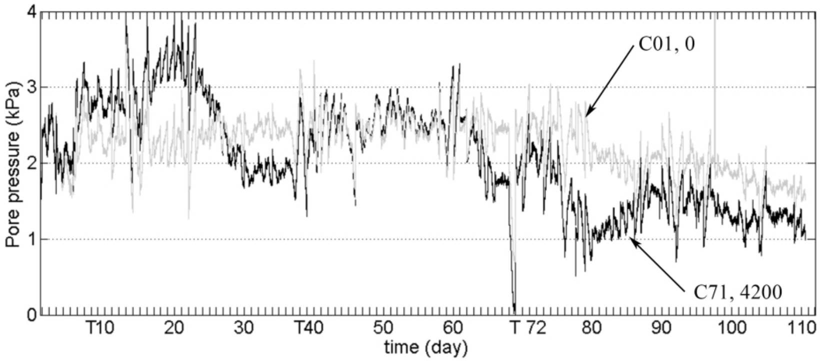
Time histories of solids content. Horizontal grey line represents the solids content of the original tailings without treatment

272x208mm (300 x 300 DPI)


Height above bottom of clumns (cm)
Solids content (%)
0
2
4
6
8
10
12
14
16
40
42
44
46
48
50
52
54
C71,4200
C72,4200
C73,4200
C92,2000
C91,2000
C93,2000
C01,0
C02,0
C81,1400
C82,1400
C83,1400

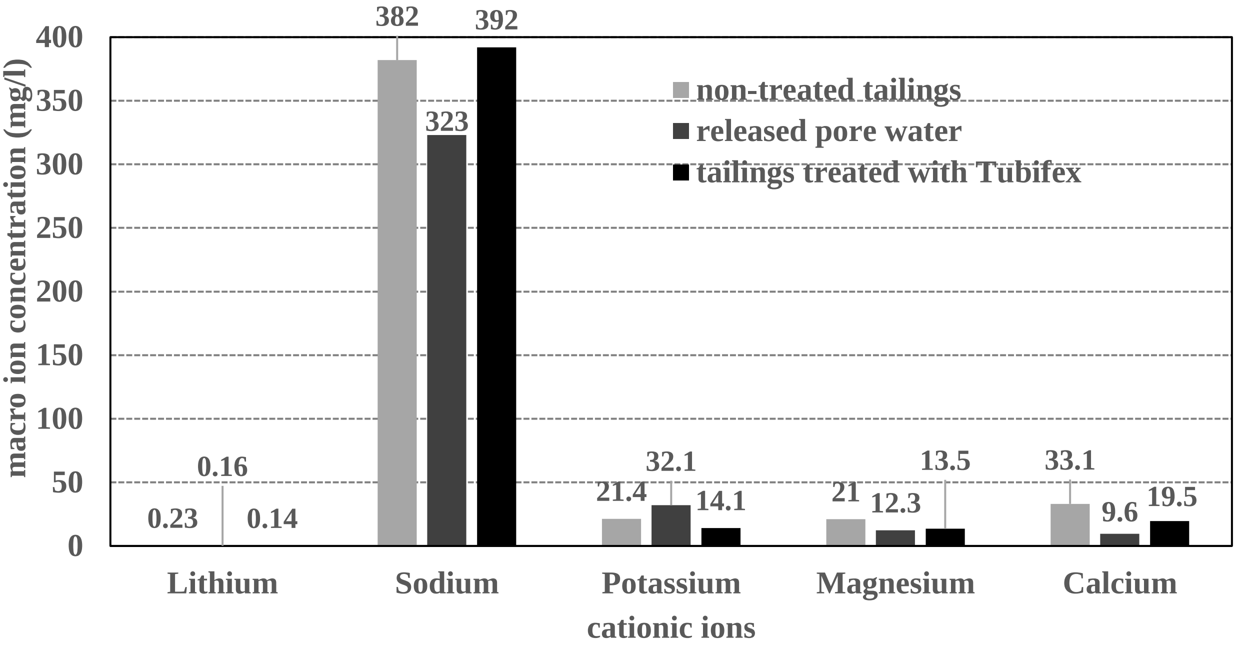

▲ 5 cm above the bottom of the column
● 5 cm below the mud surface
Undrained shear strength(Pa)
250
200
150
100
50
0
0
0
1400
1400
1400
2000
2000
2000
4200
4200
4200
Tubifex density (individuals/m2)

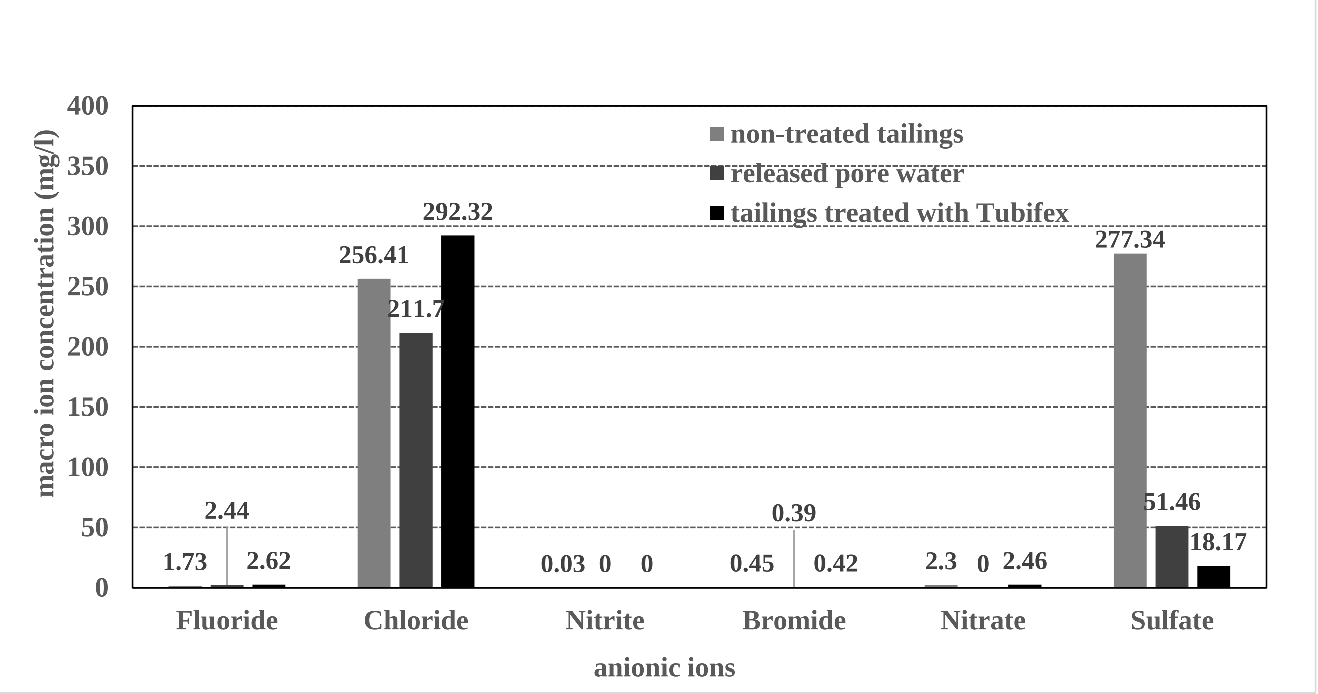

△ 5 cm below the mud surface
▲ 5 cm above the bottom of the column
Undrained shear strength (Pa)
0
50
100
150
200
250
40
45
50
55
Solids content (%)

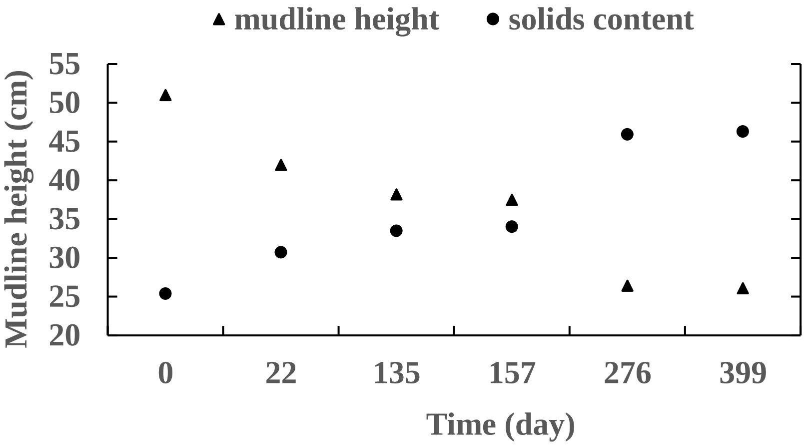


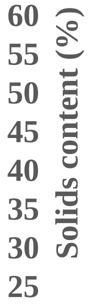
Record of pore water pressure. The symbol “T” denotes the time when Tubifex were added into columns. Piezometers were placed 11 cm above the column base

337x129mm (300 x 300 DPI)


macro ion concentration (mg/l)
400
350
300
250
200
150
100
50
0
■ non-treated tailings
■ released pore water
■ tailings treated with Tubifex
0.23
0.16
0.14
382
323
392
21.4
32.1
14.1
21
12.3
13.5
33.1
9.6
19.5
Lithium
Sodium
Potassium
Magnesium
Calcium
cationic ions


macro ion concentration (mg/l)
400
350
300
250
200
150
100
50
0
non-treated tailings
released pore water
tailings treated with Tubifex
1.73
2.44
2.62
256.41
211.7
292.32
0.03
0
0
0.45
0.39
0.42
2.3
0
2.46
277.34
51.46
18.17
Fluoride
Chloride
Nitrite
Bromide
Nitrate
Sulfate
anionic ions


▲ mudline height
● solids content
Mudline height (cm)
55
50
45
40
35
30
25
20
0
22
135
157
276
399
Time (day)


60
55
50
45
40
35
30
25
Solids content (%)


9
8
7
6
5
4
3
2
1
10
9
8
7
6
5
4
3
2
1
0