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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2017-0635.R1
Manuscript Type:	Article
Date Submitted by the Author:	19-Mar-2018
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Keyword:	Vacuum preloading, Hydraulic reclamation mud, Colloid property of tail water, Clogging of soil column, Pore-entrance size distribution
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

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Colloid effect on Clogging Mechanism of hydraulic reclamation mud improved by vacuum preloading

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ABSTRACT: Many cases of artificial soft clay foundation constructed by hydraulic filling and improved by the vacuum preloading show the clogging phenomenon in the surrounding soil, which compromise the improvement quality. To clarify the clogging mechanism and the formation of soil columns, the vacuum process was tracked from macro to micro by laboratory model tests. Results show that the soil column was formed surrounding PVD with higher strength (density) and lower water content. MIP (Mercury intrusion porosimetry) tests revealed that the pore-entrance diameter of the soil column after 50 and 43 days' vacuum ranged from 100 to 600 nm, and that at peak is 300 nm. However, the mean diameter of the colloidal particles in tail water decreases from 1000 to 100 nm with continuous vacuum application, and then becomes stable at about 100 nm after 43 day. After re-visiting the vacuum process of the hydraulic reclamation mud, the pore size distribution of surrounding soils and particle size distribution of the tail water, the clogging was explained by the filling of the pores of soil column by the colloidal particles in pore water. This mechanism differentiates the artificial foundation improved by vacuum preloading from the natural foundation for the presence of rich colloidal particles in pore water.

Keywords: Vacuum preloading; Hydraulic reclamation mud; Clogging of soil column; Colloid property of tail water; Pore-entrance size distribution

Introduction

As the rapid development of Chinese coastal city and the increase in population, the land resource becomes more and more scarce, making the marine reclamation very important. Haihua (also called seaflower) artificial island in Hainan province of south China is a typical case (**Fig. 1**), which was hydraulically filled in the sea with marine soils. However, the hydraulic reclamation mud (HRM) is artificial soft clay like slurry, needing to be consolidated prior to subsequent engineering constructions. HRM is different from natural soft soils because it is of higher water content and void ratio, leading to higher compressibility and lower mechanical strength. The HRM's clay fraction (less than 2 μm by ASTM, also including the colloid fraction) is quite high, sometimes up to 30 to 50 %, resulting in a large specific surface area, about 80-120 m^2/g (Yang 2009). On the other hand, the pore water of HRM is rich of colloids comparing with the naturally deposited soft clays, because groundwater movement reduces the salinity and mineralization of natural clays. The self-weight consolidation and infiltration of natural soft clays lead to a specific structure without presence of colloid particles (de Jonge *et al.* 2004; Lægdsmand *et al.* 1999).

Presently, the vacuum preloading method (VPM) becomes an efficient technique for improving soft clays (Chai 2011). However, some problems occur when applying this method in the foundation formed by HRM because of the formation of local dense zone (also called soil column) surrounding the prefabricated vertical drainage (PVD) as shown in **Fig. 2**. This results in an overall poor improvement quality because almost no consolidation of soils occurs outside of this zone. To tackle this

problem, lots of investigations on VPM's upgrade were carried out in last decades. Tang *et al.* (2010) observed that a thick sludge membrane, which was rich of clay fraction and with high consistency limits, was adsorbed on the PVD after the vacuum application. They attributed this phenomenon to the migration of clay fraction under large gradient of the vacuum pressure. To solve the problem, they proposed to use chemical-supported PVD to modify the surrounding soil properties and to apply lower vacuum pressure to control the gradient. Bao *et al.* (2014) investigated many cases of HRM grounds improved by VPM, and also pointed out that the severe clogging surrounding PVD was due to the high clay fraction, large fineness of PVD's filter and the fast vacuum loading rate. They suggested that the filter material of PVD, vacuum loading mode and HRM's pre-modification by self-consolidation and chemical treatment are important factors to be taken into account. Wang *et al.* (2016) and Cai *et al.* (2017) proposed a kind of anti-clogging PVD with hydrophilic membrane without concave and convex structure to overcome the clogging of PVD. Deng *et al.* (2009) proposed a ventilating vacuum method, aiming to solve the large pressure gradient to restrain the clogging effect. Wu *et al.* (2017) and Wang *et al.* (2017) introduced chemical additives (anionic, cationic and neutral polyacrylamide) into the HRM ground and found that the additives can effectively improve the improvement quality since the solid-liquid separation and the generation of the flocculants ameliorates the percolation property of the surrounding soils.

It appears from the aforementioned studies that the clogging phenomenon has been well identified from direct observation and some interesting solutions were

proposed accordingly. However, this phenomenon has not been investigated through changes of soil pore distribution. In this study, a series of laboratory model tests were carried out within the land reclamation project of Haihua artificial island (in **Fig. 1**). When vacuum was applied, the water content and mechanical strength of the surrounding soils, the pore size distribution of the clogging zone (or the soil column) were tracked. Additionally, the particle size distribution and zeta potential of the micro/nano-particles dissolved in the tail water, and the viscosity of the tail water were also investigated. Kozeny-Carman function, usually used to evaluate the hydraulic conductivity, was adopted to explicit the main influence factor of the percolation and to further clarify the clogging mechanism.

Materials and Methods

Property and artificial preparation of HRM

The original dredged HRM was from Haihua (seaflower) reclamation island in Hainan province, whose physical properties are listed in **Table 1**. The *LL*, *PL* and *PI*, determined following ASTM (2010a), are 44.8 %, 21.9 % and 22.9 %, respectively. According to the Unified Soil Classification System (ASTM 2010b), the studied HRM is low-plasticity clay (CL), as shown in **Fig. 3**. The particle size distribution, measured by ASTM (2007), is presented in **Fig. 4**, indicating that the sand, silt and clay fractions are 12.9, 57.6 and 29.5 %, respectively. The specific gravity d_s measured according to ASTM (2010c) is 2.75. The water content before vacuum loading ranges from 58% to 70%, and is about 1.5 times *LL*. In this investigation, the initial water content was preset as 67.2%, equal to 1.5 times *LL*, in order to simulate

the in-situ conditions.

To simulate the in situ HRM, the soil was first air dried, and then distilled water was added until the water content arrived at 67.2 %. The mixture was cured for 48 h to reach homogeneous moisture distribution. Afterwards, it was intermittently mixed using a stirrer also for 48 h. The prepared slurry mixture was put into the settling column for the model test.

Model equipment and experimental procedure

In the project of Haihua artificial island, the PVD was laid out squarely with a space of 1.0 m, and the PVD width is 10 cm. To investigate the improvement quality and clogging effect of HRM by VPM, a model test was developed. The internal diameter of the diacylindrical plexiglas barrel used is 28 cm. The equivalent diameter of the in situ reinforced zone is about 113 cm, hence the model similarity ratio was designed as 4.0. The in situ PVD width is 10 cm, suggesting that, the width in the model test is 2.5 cm. The height of the barrel was 40 cm, and three vacuum sensors with a maximum range of 100 kPa were pre-installed at the middle of the barrel, that is, 20 cm above the bottom of the column. The distances between the sensors and PVD in the radial direction were 3, 7 and 12 cm, respectively. The experimental set-up is sketched in **Fig. 5**. As the updated anti-clogging PVD proposed by Wang *et al.* (2016) and Cai *et al.* (2017) was applied in the vacuum preloading project at Haihua artificial island, this PVD was also adopted in the model test. It was found that almost no clay particles were adhered on the PVD after the model test.

Six parallel vacuum model tests with the same vacuum stress (100 kPa) were

carried out (in **Fig. 6**). The soil properties were determined at different vacuum periods (15, 22, 29, 36, 43 and 50 days). During vacuum application, the vacuum stress distribution in the soils was also monitored. When the vacuum periods arrived at the scheduled days, soil specimens were sampled every 1 cm far from the PVD wall at three layers situated at 10 cm, 20 cm and 30 cm from the bottom and their water contents were measured. Additionally, the strength after VPM at the above-mentioned times was determined by the vane shearing test (VST), and the dimensions of the vane are 25.4 mm diameter and 50.8 mm length. The arrangement of the above tests is presented in **Fig. 6**. In view of the investigation objectives (clogging mechanism and improvement quality), the tail water was collected and the colloidal properties of the tail water were analyzed. The pore-entrance size distribution (PSD) of the surrounding soil samples (*i.e.* soil column) was determined by mercury intrusion porosimetry (MIP).

Mercury intrusion porosimetry

The samples were taken in the zone of 4 cm from the PVD wall shown in **Fig. 6**. Freeze-drying was adopted for preparing the samples, where liquid nitrogen (-196°C) was used. Small pieces of specimens were instantaneously immersed into the nitrogen liquid. Hereafter, the frozen specimen was then transferred to the vacuum chamber for sublimation for approximately 24h. Since the soil at the early stage was very easy to be powderized, only PSD after 36-day vacuum was achieved by MIP tests.

MIP test allows the PSD determination through the relationship between the intrusion pressure and the equivalent pore-entrance diameter (Washburn 1921):

$$D = -\frac{4\gamma\cos\theta}{P} \quad (1)$$

where D is the pore-entrance diameter, γ is the surface tension of mercury, θ is the contact angle, and P is the intrusion pressure. Note that the contact angle of 140° and the mercury surface tension of 0.480 N/m were usually recommended (Deng *et al.* 2015).

Colloidal properties

As the tail water at early stage was turbid, colloidal presence was suspected. A colloid particle is usually of diameter ranging from 1 to 100 nm in the environment of solution and atmospheric environment. However, the diameter of clay colloid can extend to 1000 nm (de Jonge 2004; Stumm 1977). The clay colloid in suspension is negatively charged, resulting in flocculation and subsequently irregular formation of clay particle, further dominating the drainage. Thus, the colloidal properties of tail water are of great importance from a practical point of view (Ryan and Elimelech 1996). In this regard, Tyndall effect, zeta-potential, nano-scaled particle size distribution and viscosity are key parameters for colloidal properties.

Tyndall effect can be studied by observing scattering visible light beam when it penetrates a dispersed colloidal system. This experiment is primarily used in the laboratory for identifying colloid from the solution. When the existence of the colloidal system was confirmed, the nano-scaled particle size distribution and Zeta potential followed up. Malvern Nano-ZS nanometer laser particle size analyzer with Zeta potential function was adopted in this study. The particle size is determined by the dynamic light scattering principle and photon correlation spectroscopy. Particles

with different sizes irradiated by laser will make different fluctuation speed and intensity. This change was processed by digital correlator, and the particle size and distribution was calculated by the Stokes-Einstein equation (Assael *et al.* 2010). Zeta potential at the surface between the Stern layer and the diffusion layer is another parameter for characterizing the dispersion stability of the colloidal system. The higher the absolute value of Zeta potential, the more stable the system. On the contrary, the system inclined to coagulate and coacervate. The relationship between the Zeta potential and the stability of the colloidal system suggested by Sposito (1984) is shown in **Table 2**.

During the laboratory model test of vacuum loading, the tail water discharged from the HRM was suppressed by negative pressure into the chamber (in **Fig.5**). The collected tail water at different periods was taken for determinations of Tyndall effect, particle size distribution and zeta potential successively. Additionally, Tyndall effect of distilled water was also measured for comparison.

Results

Evaluation of improvement quality

As referred above, the model tests with preset vacuum application periods of 15, 22, 29, 36, 43, 50 days were performed, under a constant vacuum pressure of 100 kPa. It was found that the vacuum pressure of the surrounding soils changed very little after 15-day vacuum application. The pressure evolutions after 15- and 50- day vacuum application are presented in **Fig. 7**. The soil at 3 cm far from the PVD was the fastest in response to the vacuum while the slowest to achieve stability; on the

contrary, at 12 cm far from PVD the response was the latest and the stability was the fastest. The vacuum pressure at 3, 7, 12 cm from PVD came to be stable at 69, 56 and 30 kPa after about 20-, 15- and 3-day vacuum application, respectively. This observation of pressure evolution is consistent with that in field conditions (Chen 2017). Furthermore, the vacuum transmission was obviously not reached the soils at more than 7 cm far from PVD after 20-day vacuum application. However, this is rarely the case of natural foundation under vacuum loading (Mohamedelhassan and Shang 2002).

Fig. 8 shows the evolution of water content with depth, distance and vacuuming period. It appears that the water content increased with the distance far from PVD and with the distance from the model surface boundary. Further examination of the results at 20 and 30 cm from the bottom boundary shows that the water content curves after 43- and 50-day vacuuming came to coincide, suggesting that consolidation was slightly further developed and the vacuum negative pressure and clogging effect came to a balance. Note that, the gap of water content between the center and 12 cm far from PVD was about 6% after 50-day vacuuming. This evolution of water content is consistent with the consolidation process and drainage path, whilst there is a relative lower water content zone at about 4-6 cm from PVD.

Fig.9 presents the evolution of the undrained vane shear strength within the 50-day vacuuming period. The undrained vane shear strength of the soil at the bottom was slightly lower than that of the upper part. The maximum vane shear strength also increased with the vacuuming periods, that is, from 4 kPa before vacuuming, to 8 kPa

after 15 days, 12 kPa after 22 days, 17 kPa after 29 days, 24 kPa after 36 days, 30 kPa after 43 days and 33 kPa after 50 days. On the contrary, the vane shear strength of soils close to the PVD was much higher than that of soil far away from the PVD, and the differences between the center and 13 cm far from PVD were 3, 6, 9, 12, 16 and 16 kPa after 15-, 22-, 29-, 36-, 43- and 50- day's vacuuming, respectively. Note that the undrained vane shear strength of soil within the zone 0-4 cm from the PVD was quite different from that of soil at farther distance. This zone is termed as "soil column" for its obvious higher strength, higher density and lower water content.

Pore-entrance size distribution

The results presented above suggest that the soil surrounding the PVD is significantly improved. To understand this mechanism, the soil within 4 cm surrounding the PVD was sampled, and MIP tests were conducted. **Fig. 10** shows the cumulative intrusion volume curves and the density function curves. The cumulative intrusion volume gradually decreased from the values of 0.33, 0.32 to 0.31 mL/g with the vacuuming periods from 36, to 43 and 50 days. The density curves exhibit a single peak. The pore-entrance size at this peak after 50- and 43-day's vacuuming was about 300 nm, and the pore-entrance diameter mainly ranged from 100 to 600 nm. On the contrary, the pore-entrance size at peak after 36-day's vacuuming was 500 nm and pore-entrance diameter ranged from 200 to 700 nm. The density function curves slightly move towards the left, suggesting that the pore-entrance size was decreased over the vacuuming periods.

Properties of tail water

As mentioned previously, in soil science, the clay particles smaller than 1000 nm in a suspension are usually considered as the colloid fraction (de Jonge *et al.* 2014). The particle size distribution of HRM, shown in **Fig.4**, illustrates that the colloid fraction was as high as 24.5%, suggesting that colloidal particles probably migrated with tail water.

During vacuum loading, water passed through the pore channel to the PVD, and finally flowed into the tail water chamber. **Fig. 11** shows the tail water in the earlier and later periods of vacuuming. It is interesting to note that the tail water was yellow and turbid at early stage, while became clearer in the later period. This is consistent with the field observation.

To confirm the colloid existence in the tail water, Tyndall tests were first conducted. **Fig. 12** presents the Tyndall effect of tail water at the earlier and later stages and that of distilled water for comparison. There is distinctly a bright light path in the tail water whatever the suspension. However, it cannot be observed in distilled water. This confirms that colloid effect always existed in the tail water.

Fig. 13 presents the density of the particle size distribution in nano-scale of tail water at the initial suspension stage, after 15- and 43-day vacuuming. It appears that the size of colloid in the tail water ranged from 600 to 1000 nm at initial suspension state, 105 to 110 nm after 15-day vacuuming, and 85 to 105 nm after 43-day vacuuming. The colloid size became smaller and smaller along with the vacuum application. The evolution of the mean diameter of colloid in tail water with vacuuming is presented in **Fig. 14**. It is observed that the mean diameter decreased

with vacuuming period following a negative exponential function, where its tendency became slow after 43-day vacuuming.

The colloid stability in tail water is characterized by Zeta potential, and the results are shown in **Fig. 15**. Zeta potential ranged from 0 to -15 mV; but it is averagely located around -10 mV. According to previous investigation on colloid stability shown in **Table 2**, the colloid stability of the tail water was in “begin to become unstable” state whatever the vacuuming stages, suggesting that the colloid was easy to be coagulated.

Discussions on clogging mechanism

The essence of vacuum loading is the extrusion of porewater to improve soil's mechanical behaviors including enhancement in strength and reduction in deformation (Yao *et al.* 2008, Yao *et al.* 2009, Yao and Zhou 2013). Therefore, the seepage and drainage are important processes. In this regard, the hydraulic conductivity (*i.e.* k) can be used for the evaluation. Because it is impossible to directly measure the hydraulic conductivity of the curved thin soil column, to further investigate the clogging mechanism, the widely used K - C function proposed by Kozeny (1927) and Carman (1938, 1956) is introduced for this analysis:

$$k = \frac{\gamma}{\mu C_s T^2 S_0^2} \cdot \frac{e^3}{1+e} \quad (2)$$

where γ is the unit weigh of pore fluid, μ is the viscosity of fluid, S_0 is the specific surface area of soils, e is the void ratio, T is the tortuosity, and C_s is the channel shape factor. T and C_s are usually related to soil pores. Carman (1956) reported the value of $C_s T^2$ being equal to 4.86 ± 0.3 for uniform spheres. In our analysis, the value of 5 is

considered for $C_s T^2$ in the application of K - C function.

According to K - C function, the hydraulic conductivity depends on fluid viscosity, void ratio and soil's specific surface. From the cumulative intrusion volume identified by MIP test, it is observed that the void ratio of vacuumed HRM changed slightly especially in the later vacuuming period. Additionally, during vacuum loading, the specific surface area is also considered as constant.

To clarify the role of fluid viscosity in K - C function, the effect of colloidal diameter and concentration on the fluid viscosity was investigated through a cylinder deposition test. A solution with 39 % solid concentration (*i.e.* 39 g dry soil and 100 g water) was prepared and settled for 12 h. The upper, middle and bottom supernatants were drawn in turn to simulate the different colloid diameter (detailed in **Fig. 16**). Furthermore, to prepare the solution with different concentrations, the collected supernatants were dried at a low temperature of 60 °C. The particle size distribution and viscosity were then measured by the laser diffraction particle size analyzer (Zetasizer Nano ZS90, Malvern Instruments Ltd, UK) and viscometer. The result in **Fig. 16** showed that the viscosity was almost unchanged, ranging from 0.94 to 1.03 mPa·s, and the mean diameters of supernatants from upper to bottom were 495, 604 and 657 nm, respectively. Note that the mean diameters of the supernatants are slightly larger than that of the collected tailing water and the concentration in supernatants is close to that in tailing water. This finding suggests that the pore fluid with or without colloid particles, has little influence on the hydraulic conductivity.

To further clarify the clogging mechanism of the surrounding HRM or formation

of soil column, the HRM's process of vacuum loading was re-visited. Since the natural deposited soils were chronically leached by the underground water, they are structural and the colloid in pore water is rarely observed (Chen *et al.* 2009). Compared with the vacuum loading of the natural deposited soil, the colloid in porewater of HRM is richer, and moves under the gradient of negative vacuum pressure. In fact, the initial void ratio of HRM was very large, while the pore water with fine particles (clay and colloid fractions) moved toward the PVD. Under vacuuming, the soil was compressed resulting in less pore volume and smaller diameter, higher strength. But at the same time, aggregation of colloid and clay fraction occurred around the PVD, seriously clogging the drainage pores. As a result, soil column was formed and the vacuum pressure was more difficult to be transmitted radially. Note that since the pore size measured by MIP ranges from 300 to 500 nm, while the particle diameters of the colloid in the tail water ranges from 100 to 300 nm, slightly smaller than the pore size. This implies that there are larger colloidal particles accumulated in the pore channel, which was verified by **Fig. 13** and **Fig. 14** where the diameter of colloidal particles was filtered to be smaller and smaller. This filtration behavior results the clogging of the surrounding soils. Hereafter the clogging mechanism was proposed in **Fig. 17**, suggesting that there are probably two methods to overcome the clogging by dispersing the colloid in pore water or by enlarging the pore diameter of soils surrounding the PVD.

Conclusions

Vacuum loading method is widely applied to improve artificial soft clay foundations

formed by hydraulic filling. However, many cases reveal the clogging appearance in the surrounding soils and the existence of soil columns, compromising the improvement quality. To clarify the clogging mechanism and the formation of soil columns, a series of laboratory model tests were carried out and the vacuum process was tracked by different measurements, among them, the pore-entrance size distribution of the surrounding soils and the colloidal properties of the tail water were emphasized. The main conclusions were summarized as follows:

(1) The model tests showed that the vacuum transmission was obviously suppressed for the soils at more than 7 cm far from the PVD and after 20-day's vacuuming. There was a relative lower water content zone in about 4-6 cm from the PVD and the undrained vane shear strength of the soils at 0-4 cm from the PVD was much higher than that of soils far away from the PVD. This suggests the formation of soil column which is also characterized by a higher density and lower water content.

(2) The cumulative intrusion volume of the surrounding soils gradually decreased with vacuuming, from 36, to 43 until to 50 days. After 36-day vacuuming, the pore-entrance diameters ranged from 200 to 700 nm and the main pore-entrance diameter was 500 nm. After 50-day and 43-day vacuuming, the pore-entrance diameters ranged from 100 to 600 nm and the main pore-entrance diameter was 300 nm.

(3) The colloidal particles are rich in the tail water, whose diameter gradually became smaller and smaller with vacuuming. The mean diameter of the colloidal particles in tail water decreased over time before becoming stable at about 100 nm

after 43-day vacuuming. The zeta potential of the tail water was around -10 mV on average, suggesting that the colloid in the tail water was in the state of “begin to become unstable” and inclined to be coagulated during the whole vacuuming period.

(4) Since the colloidal particles slightly changed the viscosity of the pore fluid, and the specific surface area and void ratio were almost unchanged, the clogging mechanism is difficult to be explained by *K-C* function. Re-visiting the HRM's process of vacuum loading in terms of pore size distribution of the surrounding soils and the particle size distribution of colloidal particles in the tail water, allowed the mechanism of clogging by colloidal particles to be proposed.

Acknowledgements

This study is supported by the National Natural Science Foundation of China (Grant No. 51378117, 41572280, 51379131) and Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. KYCX17-0131).

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Figure Lists

Fig. 1 Haihua artificial island

Fig. 2 Soil column in situ

Fig. 3 Plasticity chart (ASTM D2487-11)

Fig. 4 Particle size distribution

Fig. 5 Laboratory vacuum preloading model tests

Fig. 6 Model test arrangement

Fig. 7 Evolution of vacuum stress

Fig. 8 Water content evolution

Fig. 9 Undrained vane shear strength

Fig. 10 Cumulative (log differential) mercury intrusion vs pore-entrance diameter

Fig. 11 Tail water

Fig. 12 Tyndall effect of tail water and distilled water

Fig. 13 Particle size distribution in nano scale

Fig. 14 Mean diameter size of the colloid in the tail water

Fig. 15 Zeta potential of the tail water

Fig. 16 Viscosity and diameter of supernatant

Fig. 17 Sketch of colloid effect on clogging

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Fig. 1 Haihua artificial island

Fig. 2 Soil column in situ

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Fig. 3 Plasticity chart (ASTM D2487-11)

Fig. 4 Particle size distribution

1.vacuum pump; 2. valve; 3. vacuum gauges; 4. plastic conduit; 5. vacuum degree test probe;
6. prefabricated vertical drainage; 7. Stainless steel support ring; 8. Tail water chamber; 9.
settling column; 10. sealing membrane.

Fig. 5 Laboratory vacuum preloading model tests

Fig. 6 Model test arrangement

Fig. 7 Evolution of vacuum stress distribution with vacuum periods

Fig. 8 Water content evolution

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Fig. 9 Undrained vane shear strength

Fig. 10 Cumulative (log differential) mercury intrusion vs pore-entrance diameter

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(a) Early stage

(b) later stage

Fig. 11 Tail water

(a) early stage (b) later stage (c) distilled water

Fig. 12 Tyndall effect of tail water and distilled water

Fig. 13 Particle size distribution in nano scale

Fig. 14 Mean diameter size of the colloid in the tail water

Fig. 15 Zeta potential of the tail water

Fig. 16 Viscosity and diameter of supernatant

Fig. 17 Sketch of colloid effect on clogging

Table 1 Physical properties of HRM

Initial water content (%)	Liquid limit <i>LL</i> (%)	Plastic limit <i>PL</i> (%)	Plastic index <i>PI</i>	Particle size distribution (%)			Specific gravity <i>d_s</i>
				Sand	Silt	Clay	
				>75µm	[75,2]µm	<2µm	
67.2	44.8	21.9	22.9	12.9	57.6	29.5	2.75

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Table 2 Relationship between Zeta potential and colloid stability (Jang *et al.*,2010)

Zeta potential	Colloidal stability
0 to ± 5	Strong agglomeration
± 5 to ± 30	Incipient instability
± 30 to ± 40	Moderate stability
± 40 to ± 60	Good stability
Over ± 60	Excellent stability

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