填 海区地下水系统内物理与化学过程之初步研究

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Preliminary studies on physical and chemical processes in the subsurface system in the land reclaimed from the sea

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Abstract

Land reclamation has played a significant role in the urban development process in coastal areas in many countries. Over the last 20 years, land reclamation has gained much popularity especially along coastal areas of the south and east China due to rapid development of industry and urbanization. While reclamation provides valuable land, it also creates various engineering, environmental and ecological problems in coastal areas. The direct impact of land reclamation on coastal engineering, environment and marine ecology is well recognized and widely studied. However, it has not yet been recognized that reclamation may change the regional groundwater regime, including groundwater level, interface between seawater and fresh groundwater, and submarine groundwater discharge to the coast. There may be various chemical reactions between the fill materials and the marine mud. These processes may result in chemicals which may have adverse effect to the coastal plants and organisms. This paper presents respectively two preliminary case studies about the possible modification of the regional flow system at Penny's Bay, Hong Kong due to land reclamation and the possible chemical reactions in the reclamation site at Shekou, Shenzhen. This paper predicts the change of groundwater system around the bay area in response to the land reclamation and the possible pathway of the contaminated groundwater below Cheoy Lee Shipyard located on the north-eastern shores of Penny's Bay. After reclamation the total groundwater head in the entire model area is increased. Due to the change of the flow system after land reclamation, the contaminated groundwater near the shipyard will not spread out much within Penny's Bay, as many people expected, but migrate northeast toward the opposite coast. At the Shekou site, the fill materials, which are largely reddish or brown decomposed granitic rock excavated from nearby hills, are dumped over the grey to dark marine mud at the sea bed. Because the coast line is extended seaward, the original seawater and groundwater interface will also move seaward accordingly. The alkaline seawater initially in the site will be gradually displaced by acidic groundwater. It is hypothesized that various chemical and physical reactions will occur in the site. These reactions may release chemicals which may have adverse effects on coastal water quality and environment. However, further studies are required to investigate these hypotheses.

Key words: Land reclamation, coastal process, groundwater flow, physiochemical reactions

1) Introduction

Most large urban centers lie in coastal regions, which are home to about 25% of the world's population. The current coastal urban population of 200 million is projected to almost double in the next 20 to 30 years. This expanding human presence has dramatically changed the coastal natural environment. To meet the growing demand for more housing and other land uses, land has been reclaimed from the sea in coastal areas in many countries, including China, Britain, Korea, Japan, Malaysia, Saudi Arabia, Italy, the Netherlands, and the United States. Since the 1840's Over 35% of Hong Kong's developed land area has been reclaimed from the sea. While reclamation provides valuable land, it also creates various engineering, environmental and ecological problems in coastal areas. The direct impact of land reclamation on coastal engineering, environment and marine ecology is well recognized and widely studied (e.g., Lee, 1998; Poon, 1997). However, it has not yet been recognized that reclamation may change the regional groundwater regime, including groundwater level, interface between seawater and fresh groundwater, and submarine groundwater discharge to the coast. These modifications will in turn cause engineering and environmental problems (Jiao, 2000; Jiao et al, 2001). There may be various chemical reactions between the fill materials and the marine mud. The original alkaline seawater in the reclamation site will be gradually displaced by acidic groundwater, which may also induce slow but complicated physicochemical processes in the reclamation site. These processes may result in chemicals which may have adverse effect to the coastal plants and organisms. This paper presents first the numerical modeling studies about the modification of groundwater flow system and transport of contaminants in a reclamation site in Penny's Bay, Hong Kong. Then some conceptual models regarding the possible physical and chemical processes in a reclamation site in Shekou, Shenzhen will be discussed. The locations of the two reclamation sites are shown in Figure 1.

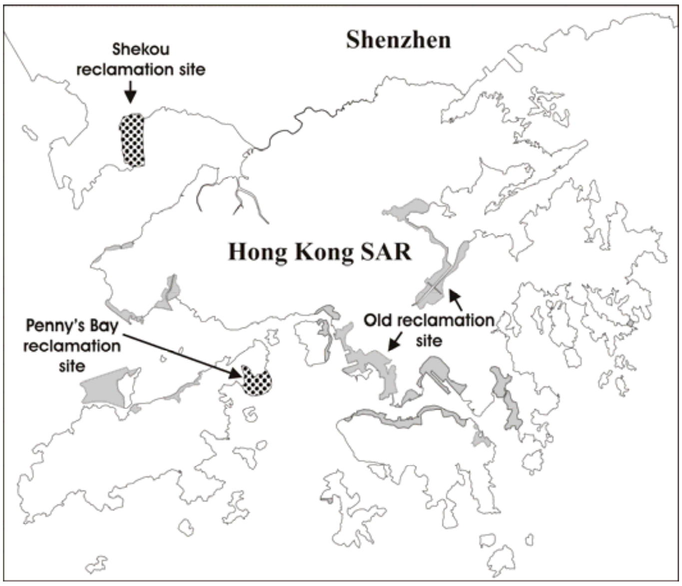

Figure 1 Reclamation sites at Penny's Bay in Hong Kong and Shekou in Shenzhen. Old reclamation sites in Hong Kong are also shown.

2) Response of groundwater flow and contaminant transport in coastal areas to land reclamation in Penny's Bay, Hong Kong

Penny's Bay at Lantau Island has been reclaimed to provide 2.8 km^2 of land for constructing a Disney theme park in Hong Kong. The works started in May 2000 and the entire works are expected to complete by the end of 2008. Over 70 million m^3 of fill material (including surcharging) will be placed in the reclamation area. The fill materials vary and can be marine sand from deeper sea deposits, river sand from Mainland China, decomposed igneous soil, construction waste, and public fill (Jiao, 2002). The elevation of final ground surface after reclamation will be about 11 mPD. The bedrock around Penny's Bay is largely feldsparphyric rhyolite. The coastal area near Yam O Wan consists of tuff. The stratigraphy of the Quaternary deposits at the site is primarily a two-fold succession of soft mud of the Hang Hau Formation overlying a complex mixture of firm to stiff silty clay with some sand and silt which forms the Chek Lap Kok Formation.

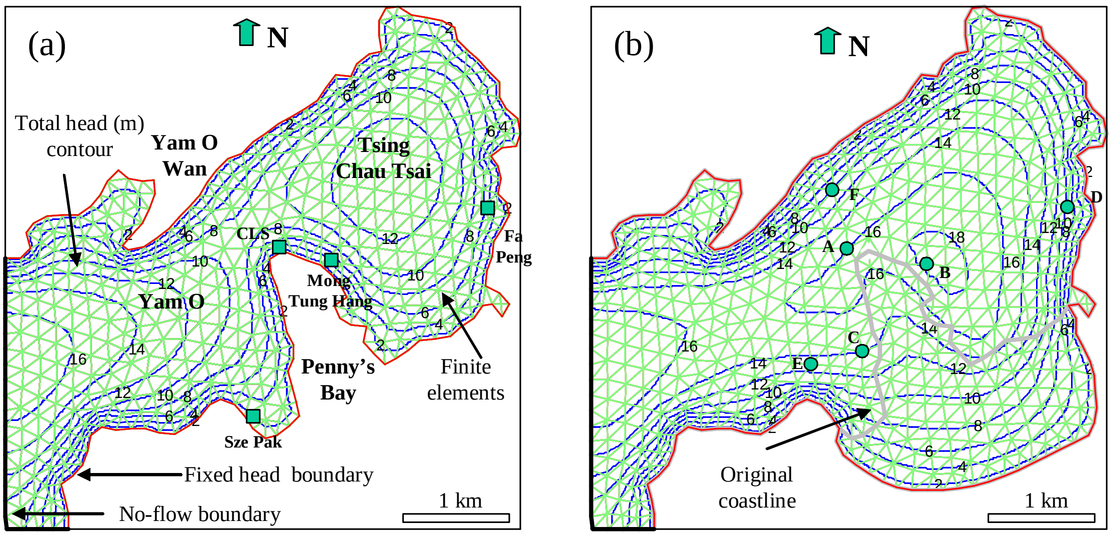

Figure 2 Total groundwater head distributions in the land area around Penny's Bay before (a) and after (b) land reclamation. The background shows the finite-element mesh used in the numerical model (from Jiao, 2002).

A former shipyard called Cheoy Lee Shipyard (CLS) was located on the north and eastern shores of Penny's Bay (Figure 1a) with a site area of about 0.19 km^2. It commenced operation in 1964 that included boat manufacture, repair and maintenance. It was reported that the soil on CLS site had been seriously polluted over the years by oils, heavy metals, dyes and organic solvents brought about by ship-breaking activities and the disposal and burning of wastes on site. It was required that the site should be excavated and the contaminated soil be removed, however, it is difficult to remove all the contaminated soil entirely. Even if the soil can be removed, the contaminated groundwater around the site may still cause problems. The migration of the contaminants into the theme park has caused a great concern of the government and the public. A modeling study was carried out to simulate the groundwater flow systems near Penny's Bay before and after the reclamation and predict the possible pathway of the contaminated groundwater originally caused by CLS (Jiao, 2002). Detailed discussion on the models can be found in Jiao (2002).

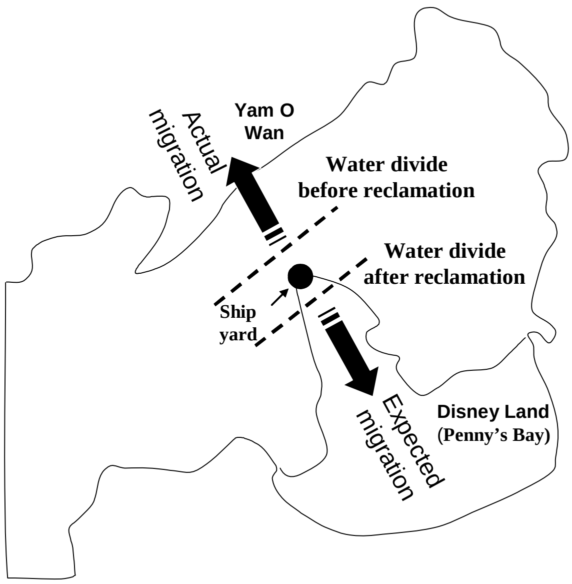

Figure 3 Shift of the water divide due to land reclamation and its impact of contaminant transport.

2.1 Groundwater system before and after reclamation

Figure 2a shows the total groundwater head distributions in the groundwater system near Penny's Bay before and after reclamation. Before reclamation, total groundwater head is high at two topographical centers near Tsing Chau Tsai and Yam O, which are located to the east and west of Penny's Bay. There is a groundwater divide between Penny's Bay and Yam O Wan (Figure 3). After reclamation, there is a regional increase in total groundwater head. The slopes around the Bay have a great increase in total head and locally the total head is almost tripled. The groundwater divide originally between Penny's Bay and Yam O Wan has moved to be within Penny's Bay (Figure 3). The high total head originally located at the hilltop of Tsing Chau Tsai has moved to areas immediately behind Mong Tung Hang, which is on the east coast of Penny's Bay (Figure 2). As can be seen from Figure 2b, a high hydraulic gradient, which indicates high seepage, toward the coastal slopes can be observed near Mong Tung Hang.

2.2 Contaminant transport in response to land reclamation

It was well believed that the contaminants from the CLS would migrate southeasterly into the theme park. To understand how the contaminated groundwater below the CLS will transport and spread out after land reclamation, transport simulation was carried out using FEMWATER (Lin et al, 1997). A source with a concentration of 100% is added to a nodal point near the location of CLS. The simulated plume after 100 years are presented in Figure 4. By that time the contaminated groundwater has reached the coastline near Yam O Wan, as shown by the contour for 5% contamination concentration. Although the CLS site is located at the coast of the original Penny's Bay, due to the groundwater flow pattern modified by the land reclamation, the contaminated groundwater will not spread significantly within Penny's Bay. Instead, it travels northeast to areas away from the Bay. The contaminated groundwater will eventually travel beyond Penny's Bay and may damage the coastal water quality near Yam O Wan.

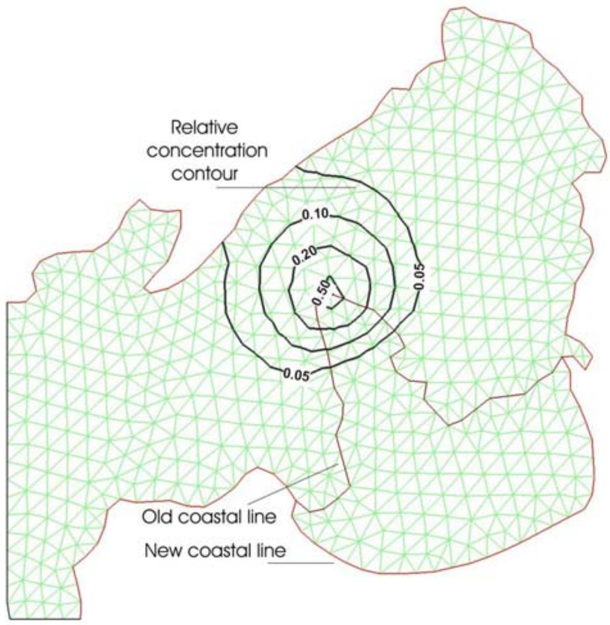

Figure 4 Predicted groundwater contaminant contours (relative concentration) of contaminants at CLS. The background shows the finite-element mesh used in the numerical model.

3) Conceptual models about physiochemical processes in a reclamation site in Shekou

Shekou is located on the northwestern coast of Deep Bay which borders Shenzhen to the north and Hong Kong to the south. Currently, a reclamation project has been carried out along part of the coast of Shekou to provide an area of over 4.6 km^2 for the construction of the Hong Kong – Shenzhen Western Corridor. The fill materials used at this site are largely the reddish completely decomposed granite (CDG) which is excavated and transported from hills nearby. There is a thick layer of dark marine mud at the sea bed. The mud may be displaced by fill and exposed to the ground surface where the seawater is shallow. What are the possible physiochemical reactions and output after the mud, fill, seawater and groundwater are mixed? What is the environmental impact of the output resulting from these reactions? Is a reclamation site a silent source of coastal pollution (Figure 4)? A research project has been undertaken by Hong Kong University with collaboration from Chengdu University of Technology to address these questions. This part of the paper will present the possible hypothetical models regarding various chemical reactions in the site. These models are to be investigated in the research project.

Table 1 Change of some heavy metals (ppm) with depth from a borehole in Shekou reclamation site

Depth from surface	Soil type	Mn	Cu	Cr	Ni	Pb	Zn
6.5 m	CDG fill	138.62	7.16	5.84	8.63	17.16	20.8
7.5 m	CDG fill	144.12	7.3	6.99	9.46	18.72	21.66
8.5 m	Marine mud	768.92	67.72	81.23	44.07	81.07	169.28
9.5 m	Marine mud	945.52	57.26	76.71	39.76	69.45	148.58
10.5 m	Marine mud	594.82	34.49	76.45	35.88	62.8	99.9

3.1 Before reclamation:

Figure 6A shows schematically the relationship between groundwater and seawater in the coastal area at Shekou before reclamation. A layer of marine mud is present in the seabed. In the study area, it is found that the marine mud is usually enriched with heavy metals and organic matters. Pyrites are identified from the scanning electron microscope images of the marine mud. Table 1 lists some of the heavy metals from soil samples taken from a borehole at the Shekou reclamation site. Heavy metals and organic matters are stored in the marine mud and are relatively stable under alkaline and anoxic condition.

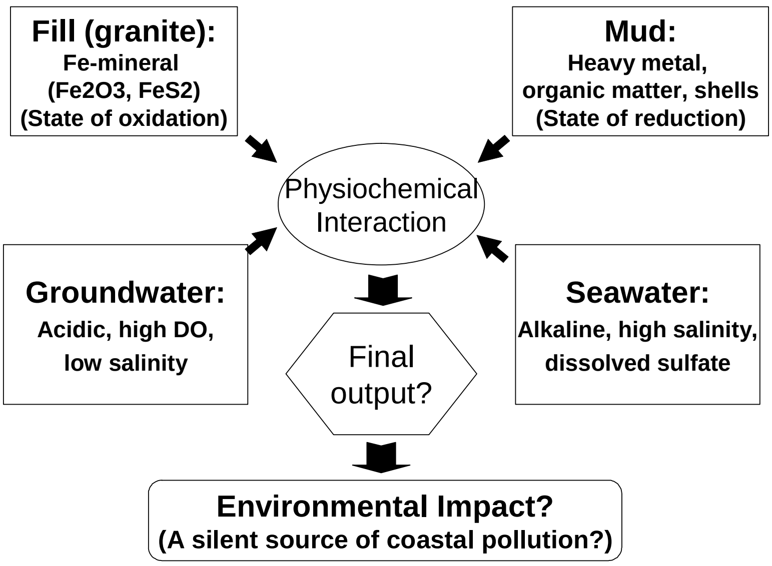

Figure 5 Physicochemical interaction of fill, mud, seawater and groundwater

3.2 Just after reclamation:

Figure 6B is the graphical representation of the situation of the subsurface environment just after large-scale reclamation was completed. It is assumed that the majority of the CDG fill materials are still soaked under seawater shortly after reclamation as the shifting of groundwater/seawater interface usually takes a long time.

When the decomposed granite is dumped into the sea and inundated by seawater, sulfate in the sea water will mix with the CDG which commonly contains iron oxides (Lefebure, 1995) and organic matter from the marine mud. The resulting chemical reaction may produce large quantities of iron sulfides in the waterlogged reclaimed land. When exposed to air, these sulfides oxidize to produce sulfuric acid (Sammut, 2001) and the reclaimed land may become acid sulfate soils (ASS).

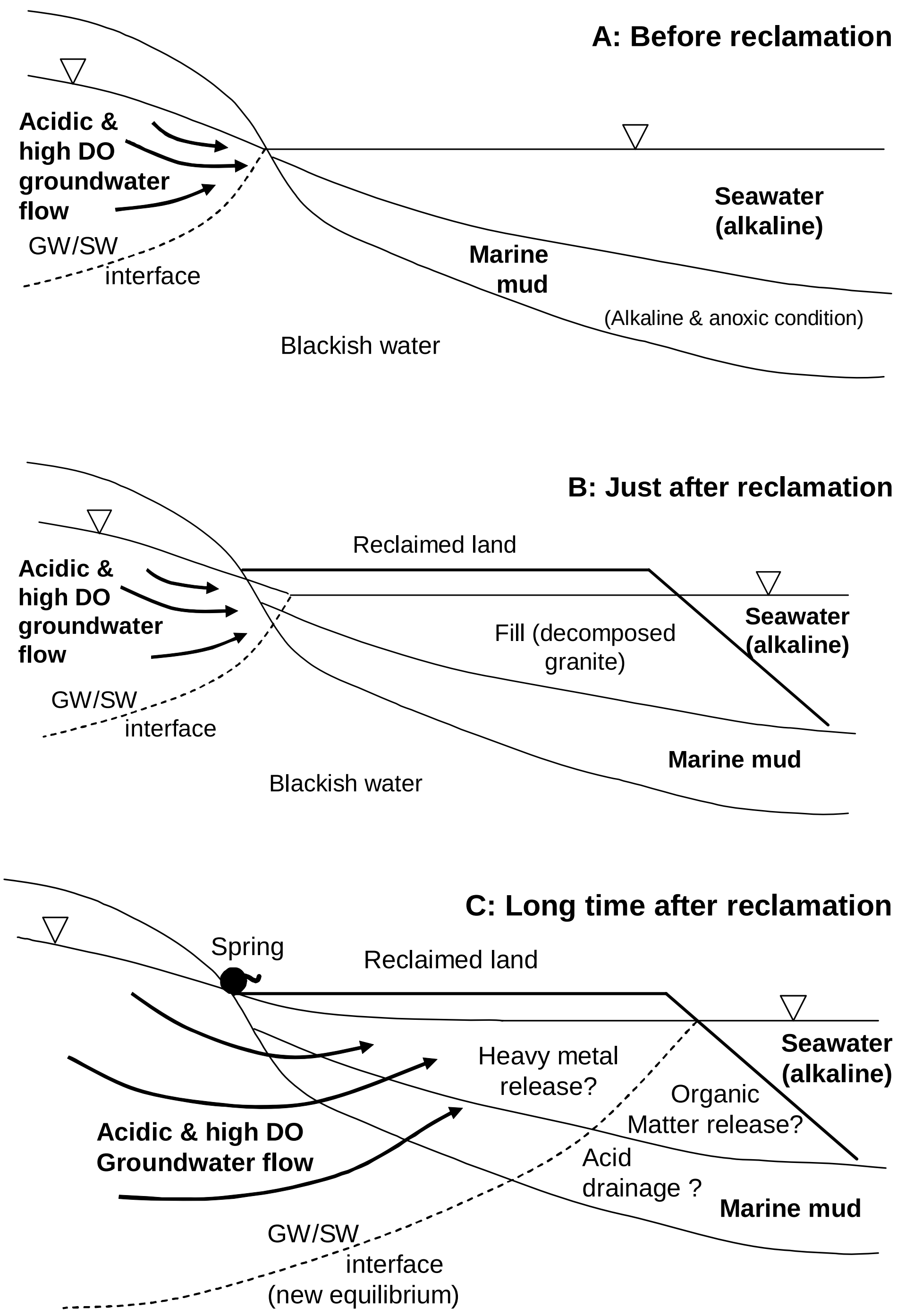

Figure 6 Conceptual models of land reclamation and possible chemical processes

In the presence of organic matters (possibly from sewage) and an anoxic environment, anaerobic sulfate-reducing bacteria could reduce the dissolved sulfate (SO_4^{2-}) (from seawater) to hydrogen sulfide gas (H_2S). Some hydrogen sulfide from sulfate reduction can be released to the atmosphere. Besides, it is possible that hydrogen sulfide can react with iron-containing minerals in CDG fill materials. Iron monosulphides (FeS) form first, but are readily converted to pyrite

(FeS_2), which is an active component of acid sulfate soils (ASS) and is stable under anoxic conditions. It is considered that AAS may be formed beneath the reclaimed land and is stable before any urban development taken place on the reclaimed land.

3.3 Long time after reclamation:

Figure 6C shows the condition of subsurface environment long after reclamation. It is assumed that the groundwater/seawater interface may shift to a new position (new equilibrium) several years after reclamation. In other words, seawater originally present in the fill materials (ASS possibly formed) and marine mud (alkaline and anoxic condition) will be replaced by fresh groundwater which is acidic and has high dissolved oxygen (DO). Any changes in the physicochemical conditions may result in some chemical changes in the fill materials and marine mud.

As mentioned, pyrite (FeS_2) is an active component of acid sulfate soils (ASS) and is stable under anoxic conditions. Air may be introduced to the soil during the coastal breathing induced by the sea tides (Jiao and Li, 2004) and pyrites in the CDG and mud may be oxidized to form sulfuric acid. The acidic leachate from ASS could possibly lead to various marine environmental problems, including the release of heavy metals stored in the underlying marine mud and eutrophication.

Besides, the gradual replacement of seawater by fresh groundwater in the reclaimed land may result in other types of geochemical reactions which could possibly lead to other environmental consequences. For example, as the salinity and pH of water in the reclaimed land decrease with time due to groundwater movement toward the sea, the dissolved iron availability increases accordingly. Iron is an important trace element for blue-green algae because it is an important constituent of the enzyme “nitrogenase” involved in nitrogen fixation. Besides, decreasing salinity usually results in increased dissolved metal concentrations because clay-organic particles from flocs with a high settling velocity.

On the other hand, marine mud, which was originally present in alkaline and anoxic condition, may possibly be flushed by acidic and high DO groundwater gradually some time after reclamation. Marine mud in the study area may be characterized by: (1) high sediment oxygen demand; (2) rich in organic compounds; (3) contaminated by heavy metals; and (4) rich in sulphide. Within sediments, there are several mechanisms for metal binding. In anoxic, sulphide and organic rich sediments, the metals will possibly be present predominantly as metal sulphide (MS), adsorbed to metal sulphide surface (metal sulphide-M^{2+}) or they may be adsorbed to organic matter (OM-M^{2+}). It is the phase in which the metal is bound that determines its behaviour and its mobilization capacity: exchangeable, carbonate, reducible and organic/sulfide phases (all of them are called non-residual phase. Residual phase = total heavy metal content – non-residual phase). Any physicochemical changes occur in sediments may affect both the speciation of metals and the stability of metal bearing phases in the sediment. In anaerobic conditions, most of the sulphur will be present as sulphide. The oxidation of both the sulphide (to sulphate) and the organic matter, which occurs once the sediment is under an oxidizing environment, may well lead to the release of metals bound to oxidisable phases. Besides, as sulphide oxidized in the sediment, pH would have decreased. Under these circumstances less metal is absorbed onto organic matter surfaces and the organic matter itself becomes structurally less complex. As discussed before, acidic leachate may be generated from the above fill materials. In addition to the influence of acidic and oxic groundwater, it is speculated that the change in pH and Eh in marine sediments may result in the release of heavy metals and/or organic matter stored in the sediments.

Marine mud is usually rich in shells and this is especially the case for the mud at Shekou. There are many oyster beds along the original coastal lines where oysters are bred and grown. Piles of oyster shells are found everywhere. After reclamation, the original coast line will move towards to the sea further. The groundwater /seawater interface may shift toward to the sea accordingly. Sediments which were originally soaked in seawater (pH > 7) may become continuously washed by groundwater (possibly pH < 7 in the study area). The acidic groundwater may dissolve the oyster shells (largely $CaCO_3$), which possibly lead to uneven ground settlement. A large amount of CO_2 gas would be generated in this process.

If the above speculations are correct, then reclamation work may result in several aspects of physicochemical changes (pH and Eh) of the seabed materials. A number of chemical reactions may take place accordingly. Further field and laboratory studies are required to test the above hypotheses.

4) Summary

Large-scale land reclamation may modify regional groundwater flow system and induce complicated physicochemical reactions. This paper presents first numerical studies on the impact of land reclamation on a simplified groundwater flow system near Penny’s Bay, Hong Kong. The modeling results indicate that there is a regional increase in total groundwater head after land reclamation. If the contaminant source at CLS is not completely removed, the contaminated groundwater may eventually migrate to the coast of Yam O Wan and have an impact on the coastal water quality, instead of moving into the future Disney Park, as expected by people who could not foreseen that the flow system would be significantly changed after land reclamation. This paper then discusses various physiochemical processes in the reclamation site at Shekou, Shenzhen. It is speculated that these processes may result in acid drainage and release of heavy metals which may have adverse impact on the coastal water quality and environment. An on-going project has been carried out to verify these hypotheses.

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