Modification of regional groundwater regimes by land reclamation

Jiu Jimmy Jiao

Department of Earth Sciences, The University of Hong Kong, P. R. China

Abstract

Land reclamation has played a significant role in the urban development process in many coastal areas in the world. While reclamation provides valuable land, it also creates various coastal engineering, environmental and marine ecological problems. These problems directly caused by reclamation have been well recognized and widely studied. However, it has not been recognized yet that reclamation will almost certainly change the regional groundwater regime, in turn causing similar problems. This paper represents the first attempt to address the impact of reclamation on groundwater regimes. It will be demonstrated that large-scale of reclamation will increase groundwater level, modify the groundwater divide, and alter submarine groundwater discharge to the coast. The change of groundwater conditions will cause engineering and environmental problems by modifying the infiltration capacity, flooding pattern, stability of slopes and foundations, interface between sea water and groundwater, and the coastal marine environment. This paper suggests that, for a major reclamation project, the change of the hydrogeological system in response to reclamation should be evaluated so that the disturbance to groundwater regimes and the damage to environment might be minimised.

Introduction

Reclamation of land from the sea has played an important role in the development of coastal areas in many parts of the world, including China, Britain, Japan, Korea, the Netherlands and the United States (Chen & Wang, 1999; Lee, 1998; Bouchard et al., 1998; Schofield et al., 1992). While reclamation provides valuable land, it also creates various engineering, environmental and ecological problems. These problems are widely investigated. For example, there are studies about the impacts of reclamation on coastal wetlands (Lee, 1998), coastal ecology (Yip, 1978) and marine environment (Poon, 1997). However, it has not been recognised yet that reclamation will almost certainly have an impact on the regional groundwater regime, in turn causing coastal engineering and environmental problems. Since the response of groundwater regime to reclamation may be slow and not so obvious, the study from this perspective has been largely ignored. Mahmood & Twigg (1995) appear to have been the first to notice that groundwater conditions may be altered by
reclamation. They report that the water table rises in, or immediately adjacent to, an area of reclaimed land in Bahrain Island of Saudi Arabia. Apart from that, there has been little study to address the impact of reclamation on regional groundwater regimes.

A research project has been initiated in the University of Hong Kong to understand the modification of the natural groundwater regime caused by large-scale reclamation in coastal areas. In this short research communication, the background of land reclamation in Hong Kong will be briefly introduced. Then, the ways in which reclamation may influence groundwater regimes, including the water level, groundwater divide and submarine groundwater discharge (SGWD), will be discussed. Attempts will be made to link the modification of groundwater conditions to slope stability, flooding and other possible coastal environmental and engineering problems.

Brief background on land reclamation in Hong Kong

Hong Kong is mountainous territory with little natural level ground other than mud-flats, mangrove swamps and marshes. Since 1841 to the present, there has been a continuous gain of developable land through reclamation and levelling of hills. Over 10% of the Hong Kong developed land area is reclaimed from the sea.

Before the mid-1950s, reclamation was essentially strip development along the coast near urban areas, straightening out the coast line by constructing substantial sea-walls and filling in the enclosed lagoons by public dumping, together with draining and filling in of some inland marsh land (Lumb, 1976, 1980). Some pre-war reclamation areas were nothing more than public rubbish dumps.

By 1955, a rapid increase in population and a heavy demand for factory space led to a new reclamation policy – filling of shallow bays and coves remote from the traditional centres – to create large industrial areas and associated housing estates. Large borrow areas had to be laid out in the nearby hills to provide fill. By terracing or platforming these borrow areas, substantial amounts of levelled land could be formed at the same time that the reclamation was being won. The fill is generally the easily excavated decomposed granite residual soil mantle, which is essentially salty coarse sand.

Since 1973, the Hong Kong Government has introduced the New Town Programme, the main objective of which is to provide land in the New Territories in Hong Kong for public housing development. Six new towns have been created and three are in the active construction stage. Much larger bays and coves are reclaimed for the creation of these towns. With full development of these towns there would be a population capacity of about 3.5 million. The fill materials are mainly marine sand extracted from the seabed.

The quality and nature of fill can be extremely variable, and there is nearly always a layer of soft marine mud on the seabed beneath reclamation sites. An attempt is usually made to displace or dredge out the mud before reclamation, but very often a layer of mud with thickness ranging from 5 to 10 m remains in place (Lumb, 1980). At some reclamation sites, such as the Tuen Mun new town site, the mud was intentionally not displaced. At another site in Sha Tin, the mud was supposed to be progressively pushed off from the site, but in actuality, the mud was reworked and very little was removed. This layer of mud is troublesome. It gradually becomes less and less permeable and leads to differential ground settlement as consolidation continues.

Submarine groundwater discharge

Coastal areas are usually the ultimate discharge zones of groundwater. The dynamic connection of the coastal groundwater and sea water has been studied by groundwater hydrologists since the 1950's (Jacob, 1950; Erskine, 1991; Jiao & Tang, 1999). Traditionally it was estimated that the amount of SGWD ranged from 0.01% to 10% of surface-water runoff. Recently, Moore (1996) has discovered that SGWD could amount to as much as 40% of the total river flow into the ocean, a surprisingly large percentage compared with the previous estimation. This finding has the potential to radically alter our understanding of oceanic chemical mass balance and suggests that groundwater input may play a very significant role in the marine environment.

SGWD can occur anywhere along the coastline or through the seabed in the form of distributed flow, but it may also concentrate locally in the form of submarine springs through fracture or fault zones or other special geological structures, just like springs formed on hill slopes on the land. A recent study, based on diving research (Marui and Hayashi, 2000), off a volcanic island in northern Japan indicates that some SGWD points occur 9 to 27 m below sea level. More comprehensive studies have been conducted on SGWD on an island in Hawaii. Light stable isotope and carbon-14 data for the deepest fresh aquifer showed that its recharge originated at an average elevation of about 2,000 m and that it had resided in the formation for about 1,800 years. Submersible surveys conducted offshore of the island also showed that the
flow through this aquifer was discharged at about 300 m below sea level (Thomas, 2000). Although there has not been any similar study in Hong Kong to date, this kind of SGWD surely exists in Hong Kong considering its large coastal areas with diverse geological conditions. If reclamation happens to block a major submarine discharge zone, such as a large groundwater-conductive fault zone, the impact on regional groundwater regimes can be profound and lasting.

Modification of groundwater regimes by reclamation

Figure 1 shows an unconfined coastal groundwater system before and after reclamation. Reclamation increases the groundwater flow path (or travel time) to the sea and reduces the groundwater discharge toward the coast. This will cause groundwater pressure buildup behind the original coastline. Groundwater may be forced to outcrop in the form of springs in the slope at the contact between the original coastline and the reclaimed land. The pressure build-up can be great if the slope is covered by chunam or shotcrete. How significant the modification due to reclamation will be depends on the permeability of the fill materials and the distance between the old and the new coastlines (or the scale of the reclamation).

An important feature of the modification is that it is slow and becomes more significant as time goes by. This is because the permeability decreases progressively with time due to gradual consolidation of fill materials and marine mud. Eventually the mud at the seabed may be so well consolidated that in places it may essentially cut off the hydraulic connection between the seawater and the groundwater behind the reclamation site. Another reason for the time-variant feature is due to gradual urbanisation over the site. More and more buildings and engineering structures will be constructed at the site. Deep foundations of
the structures will reduce significantly the horizontal permeability. The buildings, roads and pavements, and the shotcrete over the slopes near the reclamation site will reduce the over vertical permeability.

Figure 1 assumes that the groundwater divide is so far from the coast that the water divide remains unchanged after reclamation. The reclamation has an impact only on the groundwater regime of one side of the hill. When the scale of the reclamation is comparable or greater than the size of the original groundwater catchment, as often occurs in Hong Kong, the modification can be more significant. As shown in Figure 2, since the SGWD to the left after reclamation is obstructed by the fill materials, more infiltrated water will flow to the right-hand side of the hill. In this situation, the reclamation on one side of the hill may cause displacement of the groundwater divide and eventually change the groundwater conditions on the other side of the hill. The process of modification may occur over years. One day it may be found, unexpectedly, that more groundwater exists on the right-hand side of the island and that there is more SGWD to the coast on the right.

For the simple unconfined aquifer systems in Figures 1 and 2, the pore pressure build-up behind the slope may not be very significant if extra groundwater can discharge as springs at the surface. For a coastal slope consisting of weathered igneous rock in HK, the flow system can be much more complicated. Conventionally, it is believed that the permeability decreases progressively as the depth increases or as the rock becomes less decomposed (GEO, 1996). Groundwater modeling studies in Hong Kong therefore assumed that superficial soil is an unconfined aquifer and that rockhead is an impermeable boundary (Lerner, 1986; GEO, 1996). Recently it has been demonstrated, however, that the permeability distribution in a weathered profile may include a relatively high permeability zone associated with the jointed rock mass near rockhead (Jiao & Malone, 2000) and that in some
places the rockhead is chair-shaped (Jiao, 2000), as shown in Figure 3(a). If the toe of such a fracture zone is exposed at the ground surface, or is in good hydraulic communication with seawater in the form of submarine discharge, then the pore pressure may dissipate fairly quickly and there will be no significantly pressure build up even during heavy rainfall. If the discharge at the toe is significantly obstructed by reclamation, as shown in Figure 3(b), then the groundwater in such a permeable zone may be well confined, resulting in high pore pressures during exceptionally heavy rainfall periods.

**Impact of modification of groundwater regimes on coastal engineering and environment**

**Reclamation and slope stability**

If reclamation is believed to have an impact on the regional groundwater level, it is natural to speculate that it may have an adverse effect on slope stability. Rainfall is the apparent cause of most landslides in Hong Kong. Some slides are rather shallow and show an immediate response to rainfall. This is probably caused by quick and local saturation of the superficial soil in response to heavy rainfall. To understand these types of shallow landslides requires study of the movement of infiltrated water in unsaturated zones (Anderson, 1983). Some landslides in Hong Kong, however, exhibit movements well after the peak of the storm, and many are delayed by a few days. The risk levels associated with such delayed failures are high because delayed failures are unexpected. These kinds of landslide are usually deep-seated and of large scale. Most of the deep-seated landslides are, speculatively, associated with high pore pressure and complex hydrogeological conditions (GEO, 1993; Jiao et al., 1999; Jiao & Malone, 2000). Malone (1999) identified ten deep-seated landslides and discussed several features of their slope movement.

A re-examination of the ten landslides compiled by Malone (1999) shows an interesting aspect: seven

---

Fig. 3 A hillside with a confined fracture aquifer zone in a slope of weathered igneous rock (a) before and (b) after reclamation.

---

33
of them are located in slopes immediately behind major reclamation sites. This suggests that there may be a connection between reclamation and deep-seated landslides. It appears that some of the failures can be explained by Figure 3. For the hydrogeological setting shown in Figure 3, reclamation can affect the groundwater level in slopes tens of meters above the sea level. This will generate hydraulic conditions detrimental to slope stability. This hypothesis, however, requires more detailed studies.

Reclamation and flooding

It is broadly accepted that reclamation increases the possibility of flooding by modifying the pattern of surface runoff, but it is not so well known that the alteration of groundwater conditions due to reclamation can also have the same effect. Reclamation obstructs groundwater flow to the sea and a part of the groundwater becomes surface water in the form of springs at the contact between the reclamation site and the original soil.

An aquifer behaves like an underground reservoir and can receive a certain amount of rainwater. After reclamation, the groundwater table is higher and consequently infiltration capacity may be significantly reduced. More rainwater may therefore runoff directly. Meanwhile, the reclamation area is usually heavily urbanized and the surface is covered by concrete materials such as buildings, roads and pavements. The land surface impermeability will lead to weak infiltration (Foster et al., 1994) and a large portion of rainfall will become surface water directly.

Large-scale reclamations may increase the risk of flooding not only in the area around the reclaimed site, but also on the other side of a hill by elevating the water level over the entire island, as discussed earlier.

Reclamation and other possible engineering and environment problems

Modification of groundwater regimes due to reclamation may cause other engineering and environmental problems. For example, the rise of water level will lead to reduction of bearing capacity of foundations. Groundwater may also penetrate the underground concrete and cause corrosion of the steel reinforcement. The increase of water level may cause damp surfaces and superficial damage to the floor of residential buildings (Mahmood & Twigg, 1995). A significant modification of SGWD will surely have an impact on coastal water quality and the marine environment since coastal water and some species may be sensitive to groundwater input. Although the coastal water quality depends on both the surface runoff and SGWD, so far the latter has been ignored in studies of coastal water quality in Hong Kong.

Evaluation should be made of these environmental and engineering impacts before a major reclamation project is carried out, especially when such a project is next to an environmentally sensitive area such as a wetland, or near landfills.

Figure 4 illustrates the possible engineering and environmental impacts of reclamation. After reclamation, the groundwater will be redistributed and the groundwater divide will move toward the reclaimed land. Special attention should be paid to the stability of slopes near area “A”, since the build-up of the water level may be the most significant of all the slopes around the bay. After reclamation the coastline around the Dollar Bay is much shorter and there is only a very small amount of SGWD to the bay. However, the groundwater discharge to the coast near areas B and C will be increased. This will push the interface between sea water and groundwater towards the coast. The wetland on the east may become wetter since it has more groundwater input from its west bank due to

![Fig. 4 - Reclamation near environmentally sensitive areas (a) before and (b) after reclamation (the size of arrows represents schematically the magnitude of groundwater flux).](image-url)
reclamation in the Dollar bay. Whether the impact on the wetland is positive or negative depends on the groundwater quality. If the groundwater in this region is significantly contaminated, the extra groundwater input to the coastal water in areas B or C will surely damage the water quality or ecology of the wetland. Whether the impact on damage the water quality or ecology of the wetland is significantly contaminated, the extra groundwater groundwater quality. If the groundwater in this region input to the coastal water in areas B or C will surely become noticeable. How much time it will take years for the modification in the neighborhood areas beyond the bay. It may take years for the modification in the neighborhood areas to become noticeable. How much time it will take depends on hydrogeological conditions, such as the permeability of the reclaimed site, the aquifer structures, and the process of consolidation of fill and mud. It is highly possible that by the time the impact of the reclamation becomes significant in areas beyond the bay, people will not link the effects to the reclamation, having forgotten about its construction.

Summary

This paper discusses the impact of land reclamation on coastal groundwater regimes, an issue largely ignored in the literature. It is believed that the degree of modification of groundwater conditions by reclamation depends on the scale of reclamation, the permeability of the fill materials, and the hydrogeological structures of the hill slope. If reclamation is of a large scale and the permeability of the fill is low, reclamation will not only increase water level in the immediate area around a reclamation site. It will also move the groundwater divide and eventually modify the groundwater conditions through an entire island or area. Although the impact of reclamation on the groundwater regime near a reclamation site may be easily understood, the influence on coastal areas opposite reclamation sites may be ignored.

This paper also suggests that the change of groundwater conditions will in turn cause engineering and environmental problems by modifying the infiltration capacity, the flooding pattern, the stability of slopes and foundations, the interface between sea water and groundwater, and the SGWD. It is also pointed out that the modification of groundwater regimes due to reclamation is a slow process and may occur over years due to the time-dependent soil consolidation. It is suggested that for a large reclamation site, the response of groundwater regime to reclamation should be studied in detail to evaluate its environmental and engineering impacts. The concepts and speculations discussed in this paper form the basis for ongoing research carried out in the University of Hong Kong.

Acknowledgement

The study is supported by the Committee on Research and Conference Grants (CRCG) at the University of Hong Kong.

References


Lumb, P. (1976) Land reclamation in Hong Kong, Residential Workshop on Materials and Methods for Low Coast Road, Rail and Reclamation Works, Leura, Australia, September 6010, pp 299-314.


