
Preliminary assessment of the impacts of deep foundations and land reclamation on groundwater flow in a coastal area in Hong Kong, China

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Abstract Many coastal areas have been intensively urbanized because people living and working on or near coastlines are increasing. Land reclamation from the sea and high-rise buildings are common approaches to satisfying the growing needs for more housing and other land use. Coastal areas are usually the ultimate discharge zones of groundwater systems. Using a coastal area in Hong Kong as a case study, this paper discusses the change in a groundwater system due to land reclamation and construction of building foundations in a coastal area. The upper part of the study area is in a nearly natural state, whereas the lower part is probably one of the most extensively developed areas in the world. It is evident that the groundwater flow system in this area has been changed over the last century. The piezometers in the transitional zone between the natural slopes and the urbanized areas indicate significant response to rainfall and obvious upward groundwater flow. To understand these piezometric responses to rainfall, a cross section is selected for detailed study using a two-dimensional multilayered numerical model. The parameters and structure of the aquifer system are calibrated by comparing the simulated and observed water levels. To reproduce the observed behavior of the groundwater system, the model has to include two important characteristics: a highly permeable zone at the rockhead and a reduction in hydraulic conductivity of 14–20 times in the urbanized area. The sim-

ulation demonstrates that both land reclamation along the coastline and deep foundations have contributed to the modification of the flow system, but the deep foundations have the most profound impact, especially when a high conductivity zone is present at the rockhead.

Résumé La plupart des zones côtières ont été intensivement urbanisé due à la croissance de la population qui travaille et vive sur les zones littorales. La récupération des terrains sur la mer ainsi que la construction des grandes immeubles sont les moyens usuels utilisés pour satisfaire les demandes accrues de logement. D'habitude les zones côtières représentent l'exutoire final des aquifères. En utilisant la zones côtière de Hong Kong comme un étude de cas cet article analyse les changements dans les systèmes aquifères produits par la récupération des terrains et par les fondations des grandes immeubles. Tendis que la partie supérieure de la zone étudiée se trouve presque à l'état naturel, la partie inférieure représente une des zones les plus développée du monde. Il est donc évident que la circulation des eaux souterraines a été modifiée pendant le dernière siècle. Les piézomètres remplacés entre les versants et la zone urbanisée montrent une réponse significative aux précipitations ainsi qu'une hausse générale des niveaux. Pour mieux comprendre la réponse des niveaux aux pluies on a modélisé l'écoulement dans une coupe verticale en utilisant un modèle numérique multicouches. Les paramètres et la structure du système aquifère ont été calés en comparant les niveaux calculés et mesurés. Afin de reproduire les niveaux mesurés le modèle doit considérer deux caractéristiques importantes: une zone périglaciaire à grande perméabilité et une diminution jusqu' à vingt fois de la perméabilité dans les zone urbanisées. La simulation a mis en évidence que les récupération des terrains au long du littoral aussi bien que les fondations profondes ont modifié l'écoulement mais que les dernières ont l'impact le plus important surtout lorsqu'il s'agit de la zone périglaciaire à grande perméabilité.

Resumen Muchas áreas costeras han sido urbanizadas de manera intensiva, debido a la presión creciente de la gente que quiere vivir y trabajar en estos sitios. Los terrenos arrebatados al mar y los edificios de gran altura, son las respuestas comunes para satisfacer las necesidades de mas vivienda y usos nuevos para el suelo. Las áreas costeras

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son comúnmente las zonas de descarga final de los sistemas de agua subterránea. A través de un área costera en Hong Kong, tomada como estudio de caso, este artículo discute el cambio causado en un sistema de agua subterránea, debido a la recuperación de terrenos anteriormente cubiertos por el mar y a la construcción de cimientos de edificios en la zona costera. La parte más alta de la área de estudio está casi en su estado natural, mientras que la parte baja es probablemente una de las áreas más extensas en su tipo y más desarrolladas en el mundo. Es evidente que el sistema de flujo del agua subterránea en esta área ha sido cambiado a lo largo del último siglo. Los piezómetros en la zona transicional, entre los taludes naturales y las áreas urbanizadas, muestran una respuesta notable a la lluvia y un flujo evidente hacia arriba del agua subterránea. Para entender estas respuestas piezométricas a la lluvia, se seleccionó una sección vertical para estudio detallado, utilizando un modelo numérico bidimensional multicapa. Los parámetros y estructura del sistema acuífero son calibrados mediante la comparación de los niveles de agua observados y simulados. Para reproducir el comportamiento observado del sistema de agua subterránea, el modelo ha incluido dos características importantes: Una zona altamente permeable en la parte más elevada y una reducción de 14 a 20 veces en la conductividad hidráulica, dentro de la zona urbanizada. La simulación demuestra que tanto los terrenos recuperados del mar, como las cimentaciones profundas a lo largo de la línea de costa, han contribuido a la modificación del sistema de flujo, pero las cimentaciones profundas han causado el mayor impacto, especialmente cuando se presenta una zona de alta conductividad en la parte más elevada del área.

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. Land reclamation from the sea and construction of high-rise buildings with extensive foundations are two consequences of growing demand for more housing and other land uses.

Coastal areas are usually the ultimate discharge zones of regional groundwater flow systems, and large-scale land reclamation may dramatically change the regional groundwater regime by reducing submarine groundwater discharge and increasing the groundwater flow path to the sea. The construction of buildings and underground transport systems usually requires extensive foundation and ground engineering work, including deep excavation, bored piles, grouting, and diaphragm walls. The natural soil in the upper few tens of meters, which is usually a zone with the most active groundwater flow, is thus replaced by impermeable concrete. These foundation materials may also modify the regional groundwater flow

system and alter the dynamic interaction between groundwater and seawater.

Because the response of a groundwater regime to land reclamation and deep foundations may be slow and not so obvious, this phenomenon has been largely ignored. Gehrels et al. (1994) studied lakes or polders reclaimed in Netherlands by building a circular dyke and then pumping out the enclosed water and believed that these reclaimed lakes may be a reason for groundwater level decline in the Netherlands' lowlands during recent decades. Stuyfzand (1995) discussed further that the reclaimed lakes in a coastal plain in the Netherlands may impose changes in the groundwater flow pattern and groundwater quality and speculated that the changes may occur over tens of years due to the sluggish movement of groundwater. Mahmood and Twigg (1995) reported that, from statistical analysis of water table variations in Bahrain, the water table rose under areas associated with land reclaimed from the sea.

Hong Kong is a mountainous territory with little natural level ground. Since 1841 to the present there has been a continuous increase in developed land through reclamation and levelling of hills. Up to 1995, nearly 35% of the developed land in Hong Kong had been reclaimed from the sea (Civil Engineering Office 1996). The steep terrain in Hong Kong has forced 90% of the 6.7 million people to congregate in just 165 km², creating the highest population density in the world. The modification of regional groundwater regimes in Hong Kong by reclamation was discussed by Jiao (2000) and Jiao et al. (2001). Jiao et al. (2001) derived analytical solutions for groundwater table variations due to land reclamation along coastal areas. The solutions show that modification of the groundwater regime by land reclamation is mainly influenced by the scale of reclamation and the hydraulic conductivity of the fill materials. The possible damming effect of a basement structure on groundwater flow was first mentioned in Hong Kong (GCO 1982). Pope and Ho (1982) further examined the effect between two piles using a simple numerical model, and Brassington (1996) demonstrated schematically that pile foundations, especially in urban areas, can radically reduce the cross-sectional area of shallow aquifers and may result in changes of the groundwater level.

Studies on the effect of human activities such as land reclamation and deep foundations on natural groundwater flow system are of not only theoretical significance but also practical implications. Land reclamation and deep foundations may reduce submarine groundwater discharge, which may in turn change the coastal seawater quality, and increase the water table in the coastal areas, which may impact the foundation stability of the coastal structures. Hence, both the theoretical and practical problems associated with the effect of land reclamation and foundations provide the motivation to begin developing an understanding of the modification of the flow system due to land reclamation and deep foundations. It is believed that a better understanding of these effects is conducive to the planning, design and maintaining sustainable development in coastal urbanized areas. This

research will also provide methodology and experience to predict and evaluate the change of groundwater systems and its environmental impacts in response to large-scale reclamation and extensive urbanization in Hong Kong and elsewhere in the world.

A research team in the Department of Earth Sciences, the University of Hong Kong has carried out a series of studies on coastal hydrogeological phenomena with special reference to Hong Kong (Jiao and Tang 1999; Nandy and Jiao 2001; Jiao and Li 2004). In this paper the preliminary results of research is presented on how regional groundwater systems are affected by land reclamation and construction of building foundations. Using a case study in the Mid-Levels part of Hong Kong, an area on the north-facing slopes of Victoria Peak on Hong Kong Island, the changes in groundwater flow in response to land reclamation and construction of deep foundations in an extensively urbanized coastal area is discussed. The slopes in the study area have a history of instability, including a major landslide at Po Shan in 1972 that killed 67 people. In order to understand the factors affecting future housing development, the Geotechnical Control Office (GCO) (now Geotechnical Engineering Office (GEO)) of Hong Kong organized a two-year geotechnical study of the area, which involved an assessment of the geology, hydrology and engineering characteristics of the soils and rocks mantling the slopes (GCO 1982). The Mid-Levels study represents the first and still the most comprehensive study related to hillside hydrogeology in Hong Kong and provides valuable geological and hydrogeological data for future development.

Starting about 1955, urban development or redevelopment in Hong Kong began on a large scale and by the 1980s the study area was largely urbanized. As a result of urbanization in Hong Kong Island over the last century, most coastal springs have disappeared and the seepage zone has moved uphill. Piezometric data available from the Mid-Levels study indicate that there is an upward groundwater flow zone in the transitional region between the upper natural slopes and the urbanized areas. Deep groundwater in the urbanized area is well confined. These observations indicate that the downhill movement of groundwater has been significantly reduced as shown by the extinct springs at the coast; instead, groundwater is forced to flow upwards at the middle of the hill slopes. It is hypothesized that the natural groundwater flow system has been significantly modified by urbanization activities such as land reclamation and construction of deep foundations. Numerical simulation is carried out to test this hypothesis.

Site Background

Geology

The study area in Hong Kong is centered on the Mid-Levels, which is between the natural steep slopes of Victoria Peak and the coastal areas of the Western District (Fig. 1). The lower part of the area is probably one of the most intensely developed areas in the world, with nu-

merous skyscrapers along the edge of Victoria Harbour, whereas the upper part of the area has natural slopes with well-developed vegetation. A long history of engineering activities has resulted in hundreds of boreholes in this area that provide valuable information on the three-dimensional geology.

The weathered profile on igneous rocks in Hong Kong is divided into 6 grades, designated I to VI, ranging from fresh, to slightly decomposed, moderately decomposed, highly decomposed, completely decomposed to residual soil (GEO 1997). Grades I to III are usually called bedrock and Grades IV to VI engineering soil. Figure 2 shows a simplified geological cross-section from the Peak to the Harbour. This area consists of volcanic rocks with a granite intrusion located in the lower slopes. The irregular contact between the granite and volcanic rocks crosses the study area and is disrupted by faults in several locations (Fig. 1). The slopes are covered by colluvium, varying from zero to 5–20 m in mid-slope, which was mostly derived from the volcanic rocks on the higher slopes. The depth of weathering in the granite below the colluvium cover varies from 2–3 m in the upper slopes to depths of over 50 m in the lower slopes. The colluvium and well decomposed rock above the bedrock has an average thickness of less than 30 m.

Hydrogeology

In the Mid-Levels study, the subsurface materials were generally grouped into three aquifer units (GCO 1982): (a) colluvium, (b) highly to completely decomposed volcanic rock and granite (Grades IV–VI), and (c) volcanic and granitic bedrock (Grades I–III). The colluvium contains transient and permanently perched water tables. The main water table is in the decomposed rock aquifers together with the bedrock aquifers (GCO 1982). The estimated hydraulic conductivity shows that there is no appreciable difference in hydraulic conductivity between the granite and volcanic rocks (GCO 1982). The contact zone between the two rocks does not appear to have any obvious hydrogeological effect. Randall and Taylor (1982) showed that the faults apparently do not significantly affect groundwater levels or piezometric responses in the Mid-levels area.

Over 400 boreholes were drilled in the Mid-levels area and hydraulic conductivity tests were conducted. The hydraulic conductivity test data obtained from various sources were grouped on the basis of depth from the ground surface or the degree of weathering (GCO 1982). Although the scatter was very large, a general conclusion was drawn that the hydraulic conductivity decreases progressively as the depth increases or as the rock becomes less decomposed. This pattern has been adopted in GEO guides (GEO 1994) and widely used in Hong Kong. Either a gradual or step decrease in hydraulic conductivity with depth can only lead to an unconfined aquifer model. As the regionally influential and internationally cited Geotechnical Manual For Slopes states (GEO 1994, p. 55), “in Hong Kong, aquifers are usually unconfined”.

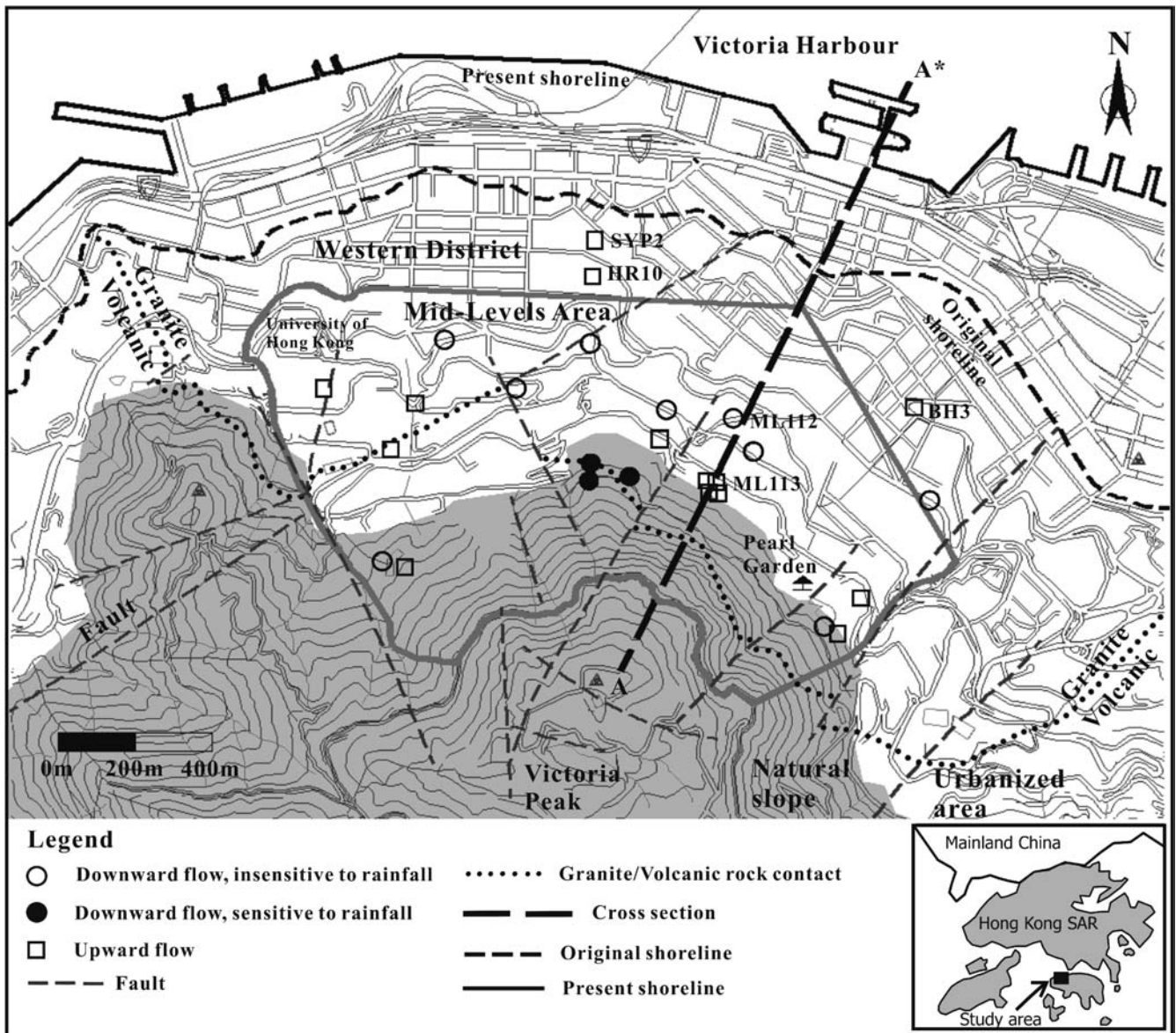


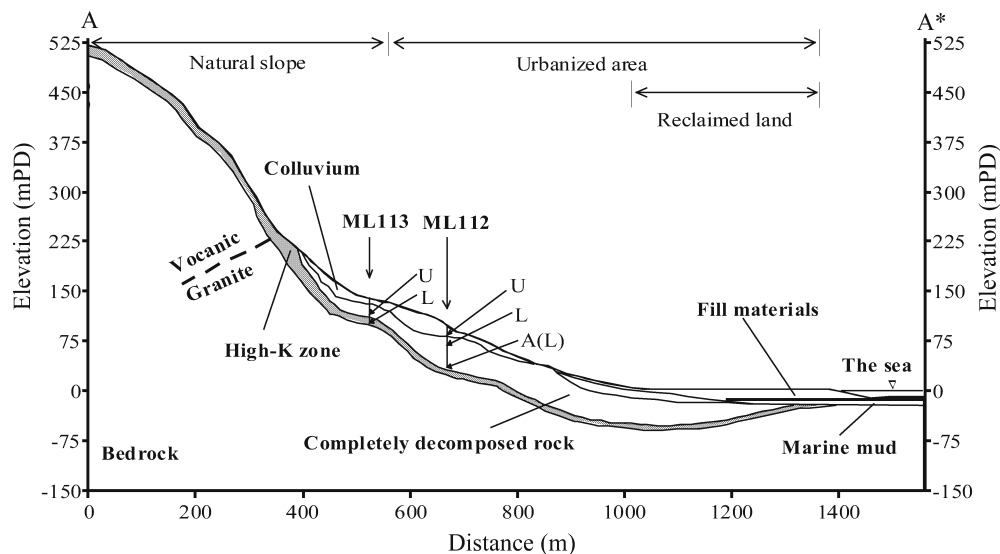
Fig. 1 Simplified topography and geology of the study area (inset showing location with respect to Hong Kong and Mainland China)

Possible High Hydraulic Conductivity Zone at the Rockhead

Average hydraulic conductivity values vs. depth or degree of weathering in weathered igneous rocks, which are usually very heterogeneous, over a large slope area such as the Mid-Levels may be misleading. The simple mathematical average of the measured hydraulic conductivity data will tend to underestimate the overall hydraulic conductivity of the rock mass. A fracture zone will have the greatest effect on groundwater movement, however due to low fracture density, the possibility that a borehole will intercept a fracture zone is very low. The averaged hydraulic conductivity value cannot be representative of overall hydraulic conductivity of the mass weathered rock without giving more weight to large measured hydraulic conductivity values, such as those associated with fracture zones.

After reviewing published hydraulic conductivity data, groundwater behavior, and piezometric responses to rainfall in Hong Kong, Jiao and Nandy (2001) re-examined the possible hydraulic conductivity profile in igneous rocks in Hong Kong. They demonstrated that, at least in some places, a relatively high hydraulic conductivity (K) zone (denoted as HKZ hereafter) may exist at depth at or near the rockhead due to a well-developed fracture network. For example, the vertical hydraulic conductivity profile from many boreholes in a small construction site ($60 \times 40 \text{ m}^2$) shows that hydraulic conductivity increased from 10^{-6} m/s in completely decomposed rock (denoted as CDR hereafter) to 10^{-5} m/s at the rockhead (Davies 1987). A series of constant head water extraction tests in the Central District, which is on the east side of the study area, show that CDR at a depth of 10 m above rockhead

Fig. 2 Conceptual hydrogeological cross-sectional model along A-A*



has an average hydraulic conductivity of 6×10^{-6} m/s whereas close to rock head it is 6×10^{-5} m/s.

The groundwater flow regime in such a relatively high permeability zone may be confined, resulting in higher water pressure rise in response to rainfall than might otherwise be expected. This conclusion has been confirmed by the artesian groundwater flow observed in the lower part of the Mid-Levels area. The water level in BH3 (Fig. 1), a borehole drilled close to the bedrock in the lower part of this area, rose up to 3.7 m above the ground surface (Jiao et al. 2003). This indicates that the highly decomposed rock or saprolite (Grades V and IV) below the colluvium can be regarded as a semi-confining unit for the confined zone at the rockhead. This unit is rich in clay content. As recently demonstrated by Campbell and Parry (2002), kaolin concentrations commonly occur in relict discontinuities in saprolite (Grades V and IV material) in weathered rocks in Hong Kong.

Uphill Movement of Seepage Zones in the Process of Urbanization

In the past, the coastal areas of Hong Kong such as the Western District (Fig. 1), which is less than 30 m above Principal Datum (mPD), used to be centers of plague and illness because of the shallow groundwater and numerous springs. In a government report written in 1888 to enquire into the cause of the fever prevailing in the Western District, which was directly on the coast at that time (Fig. 1), the damp soil and shallow water table in this area were taken as the cause of the disease: "The situation of the houses in the Western District is such that malarial fever might be expected to develop around them. The houses stand at the base of a high hill receiving tropical rainfall. Around the houses numerous springs exist, and at no great distance from the surface, sub-soil water is found standing; in addition, in many places the water finds its way to the surface causing pools in some instances and in others a damp soil" (Hong Kong Government 1888).

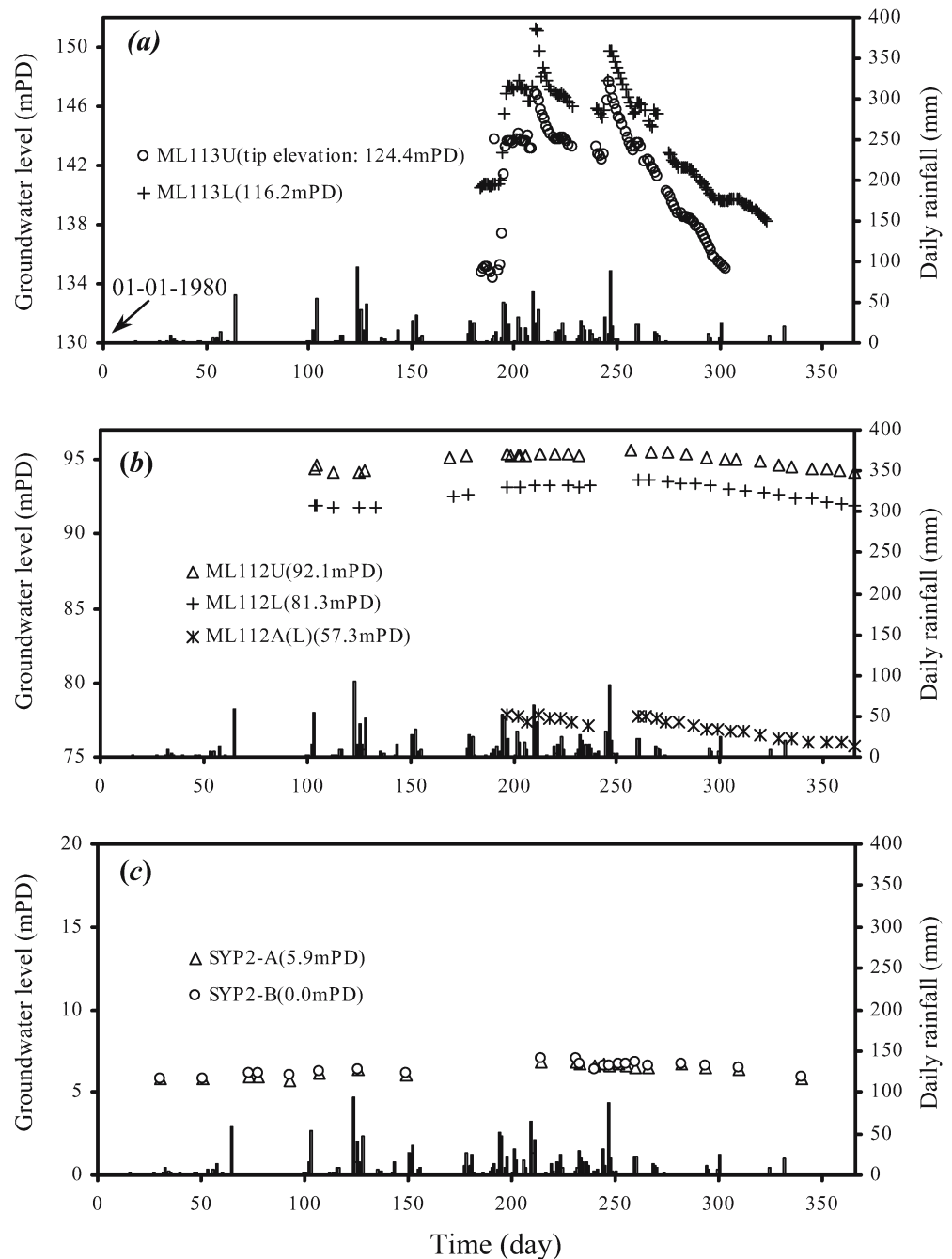
From this old report, it is clear that the Western District used to be an active groundwater discharge zone with groundwater level near or at the ground surface. It is also believed that in the early days the local communities relied on springs and seeps as potable water supplies. Some springs were the main water sources for local communities even during the driest year of 1963. This indicates a normal downhill groundwater flow system: water is recharged at the upper part of the slope and then discharged to the sea or to ground seeps in the coastal area.

However, most coastal springs have become extinct in the last half century. In the Mid-Levels study, seepage locations were surveyed in the Mid-Levels and its neighborhood areas. Most of the seepage points were located between the elevations of 40 and 240 mPD (GCO 1982). Interestingly, almost no seepage points were observed in the Western District. The disappearance of these coastal seepages may be related to urbanization that effectively sealed the ground surface, but it may also be due to retardation of downhill groundwater flow by deep building foundations. Meanwhile, some buildings such as the Pearl Garden at 180 mPD (Fig. 1), which is near the transition zone between urbanized area and the natural slope and used to be founded on soil above the water table, now suffer from wet or flooded basements, especially during the rainy season.

Piezometric Response to Rainfall

The different water level response to rainfall of 1980 in about 20 piezometer clusters (Fig. 1) installed by GCO in the Mid-Levels was examined. This was a dry year since the annual rainfall in 1980 was 1,510 mm, which is much lower than the average annual rainfall of 2,200 mm. Inside the natural slopes, most of the piezometers with tips at different depths show a vertically downward groundwater flow and some are fairly sensitive to rainfall, which is expected in a rainfall recharge zone. Near the transitional zone between the natural and urbanized areas, most

Fig. 3 Observed groundwater levels in 1980 at piezometer groups of ML113 (**a**), ML112 (**b**), and SYP2 (**c**) (Note that piezometric data were read from graphics collected from the public section of the Library of the Civil Engineering Department, Hong Kong Special Administrative Region Government)



piezometers show an upward flow and are sensitive to rainfall. Such an upward flow indicates that the downhill groundwater movement is somehow retarded. As a typical example, the response of the piezometer group ML113 is shown in Fig. 3a. The location where residential buildings such as the Pearl Garden have flooded basement coincides with the areas with upward flow.

In the extensively developed lower part of the Mid-Levels, most of the piezometers show a downward flow and are insensitive to rainfall. A typical example is ML112 which is shown in Fig. 3b. It seems that the groundwater flow in the urban area is sluggish and that

overall only has weak hydraulic connection with the recharge area at the natural slope.

Piezometers installed in the coastal area such as SYP2 and HR10 show an upward flow again but are insensitive to rainfall (Fig. 3c). BH3, a deep borehole installed recently, shows that the water level is 3.7 m above the ground surface (Jiao et al. 2003). This feature shows that the deep groundwater in the coastal areas is under confined and even artesian conditions.

It is evident that the groundwater flow regimes can be divided into four zones: downward flow in the natural slope, upward flow at the transitional area, downward flow zone in the middle of the hill, and upward flow again

along the coast. We speculate that the uphill movement of the seepage zone and the upward flow in the transitional area between the natural slope and the urbanized area may be related to urbanization activities such as land reclamation and construction of deep building foundations.

Land Reclamation and Deep Foundations

Reclamation of Land From the Sea

Land reclamation has played a significant role in the urban development of coastal areas in Hong Kong. Several land reclamation projects have been carried out along the coast in the study area since 1841 (Fig. 1). Before the mid-1950s, reclamation was essentially strip development along the coast near urban areas, such as the coastal areas of Hong Kong Island, by constructing substantial seawalls and filling in the enclosed lagoons by public dumping (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 larger reclamation projects. Large borrow areas had to be developed 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 taking place in the coastal areas. The fill was generally the easily excavated residual soil mantle on decomposed granite, which is essentially coarse silty sand.

The permeability in a reclamation site is extremely unpredictable and varies with the nature of the fill materials and the method of placement. For fill composed of CDR (completely decomposed rock) and marine sand, permeabilities can be on the order of 10^{-4} or 10^{-5} m/s, but permeabilities of compacted fill composed of completely decomposed granite and volcanic rocks can be 10^{-6} – 10^{-7} and 10^{-6} – 10^{-8} m/s, (GEO 1993). Although the quality and nature of fill at the site can be extremely variable, there is usually a layer of soft marine mud at the seabed beneath reclamation sites. The permeability of this marine mud is usually extremely low, with a range of 10^{-7} – 10^{-9} m/s (Kwong 1997). This layer of mud is usually troublesome and it gradually becomes less and less permeable as consolidation continues.

Deep Foundations of Buildings

In Hong Kong, a majority of the 6.7 million people reside in a narrow strip less than 1 km from the sea and this leads to intensive urbanization in the coastal areas of Hong Kong Island. Urban development or redevelopment in Hong Kong began on a large scale in 1955 (Lumb 1980). The previous height restrictions on buildings were relaxed and tall buildings, now so characteristic of Hong Kong, became the norm. Foundations had to be more substantial than in the past and the practice soon developed of blanketing the site with long piles at the closest allowable spacing, in effect “saturation piling”.

Since the 1960s when the price of land became high, taller and taller buildings become economical. Typical

buildings changed from 20–25 storeys in the 1960–1970s to 30 storeys in 1980s. The saturated piling solution was gradually superseded by large diameter pier foundations ranging from 1.2 to 3.2 m (Lumb 1980). Urbanization in this area was largely completed by the 1980s, although some redevelopment continued after that. The length of the piers ranges from 20 to 50 m, depending on the depth to bedrock. Diaphragm walls and silicate grouting at the bottom of the walls are commonly used along the perimeter of a construction site to cut off inward water flow. Consequently, after a building is constructed, a “concrete box” of low hydraulic conductivity is left in the soil. The natural soil in the upper few tens of meters, which is usually a zone with the most active groundwater movement, is then largely replaced by foundations and other construction materials.

Numerical Simulation

A cross-sectional numerical model through ML113 and ML112 was constructed in an attempt to understand the impact of urbanization activities such as land reclamation and deep foundations on groundwater regimes. The model will reproduce the piezometric response of the two piezometer groups of multiple tips at different vertical locations. Among the piezometer tips, ML112U is in colluvium; ML112L, ML112A(L), ML113U are in CDR, with ML112A(L) very close to the rockhead; ML113L is in the rockhead. Detailed locations of the tips are shown in Fig. 2.

Conceptual Model

The 2D cross section (Fig. 2) includes a complete hydrogeological system from the water divide at Victoria Peak to the coastline of Victoria Harbour. The structure and thickness of the model layers are based on the actual geological structure except for the HKZ (high hydraulic conductivity zone). Although it is speculated that there must be a highly permeable zone along the rockhead, there is no detailed information on the thickness and the distribution of the HKZ. In the cross section model, the HKZ is represented by a 10-m-thick layer located immediately below the rockhead.

As demonstrated by field permeability tests, the colluvium and alluvium is more permeable than the completely to highly decomposed in-situ rocks. Thus, a greater hydraulic conductivity value is given to the superficial soils than to the CDR. The solid bedrock underlying the HKZ below the rockhead is given a very low hydraulic conductivity value. The bedrock below –150 mPD is treated as an impermeable boundary.

Governing Equation

The governing equation of two-dimensional flow for an unsaturated and saturated system can be written as follow

$$\frac{\partial}{\partial x} \left(K_x(h) \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial z} \left(K_z(h) \frac{\partial H}{\partial z} \right) + Q = S(h) \frac{\partial H}{\partial t} \quad (1)$$

where x , z are relevant horizontal distance and elevation, respectively (m); t is time (s); H is hydraulic head (m); Q is source or sink term (m/s); $K_x(h)$, $K_z(h)$ are horizontal and vertical conductivities (m/s) dependent of matric suction. Due to limited data in this study, it is assumed that $K_x(h)=K_z(h)=K(h)$; h and $S(h)$ are matric suction head (m) and specific storage of pore water (1/m), which can be expressed respectively as:

$$h = \begin{cases} z - H, & H < z, \text{ Unsaturated} \\ 0, & H \geq z, \text{ Saturated.} \end{cases} \quad (2)$$

and

$$S(h) = \begin{cases} C(h) = -\frac{\partial \theta}{\partial h}, & h > 0, \text{ Unsaturated} \\ S_s, & h = 0, \text{ Saturated.} \end{cases} \quad (3)$$

where $C(h)$ is the storage capacity of unsaturated materials (1/m); θ is the volumetric water content (dimensionless); S_s is the specific storage of saturated materials (1/m).

Mesh System, Boundary and Initial Conditions

A finite-element mesh mixed with triangular and quadrangular elements is designed to adapt the irregular structures and shapes of the multilayer aquifer system. Elements are fine in the shallow part of the model area where groundwater is the main concern of this study and gradually become coarse toward the bottom. Total numbers of elements and nodal points are 1,765 and 1,774, respectively.

The left boundary is chosen to be at the water divide and is represented by no-flow boundary. Submarine groundwater discharge is usually significant only in the offshore area near the coast. Toward the right, the lateral groundwater discharge in the deep layers to the sea is progressively weaker as the layers are buried deeper and deeper. A non-flow boundary is set at about 200 m from the coastal line. The bottom no-flow boundary is set to be at 150 mPD, which is much lower than the depth of the rockhead. The nodes on the seabed at the top-right are treated as constant head boundaries. Other ground surface boundary conditions are treated as prescribed flux (infiltration rate). It is reasonably believed that such a model domain includes a complete hydrogeological system.

The maximum hydraulic head of a node at the ground surface is set to be the ground level. The observed data covers a period of over 200 days starting from April 1980. The model is first run for a steady state to provide the initial water level for the transient flow model at the beginning of 1980. In the steady state model, the infiltration rate is based on the average daily rainfall of 1979 in Hong Kong Island.

Model Parameters

Although the model includes both saturated and unsaturated flow, the focus is the saturated flow because it is believed that unsaturated flow is less important in such a fairly large-scale hillslope model. Most of the parameter values are available from various sources, but it is believed that these estimated values couldn't be used directly in the model but to provide initial guesses. The aim of this study to understand qualitatively the possible existence of HKZ (high hydraulic conductivity zone) and the impact of the deep foundations and land reclamation on the flow system using a quantitative approach. Because of limited observational data, only some key parameters can be calibrated by comparing the simulated water level with the observed ones at ML112 and ML113.

Infiltration Rate

The percentage of rainfall that infiltrates the ground surface, the infiltration coefficient, is a very important parameter but it is usually difficult to estimate. The infiltration coefficient for the upper part of the Mid-Levels area is estimated to be 34% (GCO 1982), whereas Li (2003) reported 59–75% infiltration on a saprolite slope in Hong Kong. The Geotechnical Manual for Slopes (GEO 1997) suggested an average of 50% infiltration for Hong Kong, and this is the value used for the upper natural part of the slope. In the developed part of the area with high degrees of urbanization, there is no measured infiltration rate available. To take into account the fact that this region is progressively covered by more and more concrete surfaces toward the coastal line, infiltration coefficients are taken as 20% and 5% for the lower Mid-Levels and the coastal areas, respectively.

Aquifer Hydraulic Parameters

The unsaturated soil/rock hydraulic properties, $\theta(h)$, $K(h)$, can be described by empirical equations. The expression of van Genuchten (1980) is given by

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha_w h|^{n_w}]^m} \left(m = 1 - \frac{1}{n_w} \right) \quad (4)$$

where θ_s and θ_r denote the saturated and the residual water contents, respectively; α_w and n_w are independent parameters. Gardner (1958) suggested the function $K(h)$ as follows

$$\frac{K(h)}{K_s} = \frac{1}{\alpha_k h^{n_k} + 1} \quad (5)$$

where K_s is the saturated hydraulic conductivity; α_k , n_k are independent parameters.

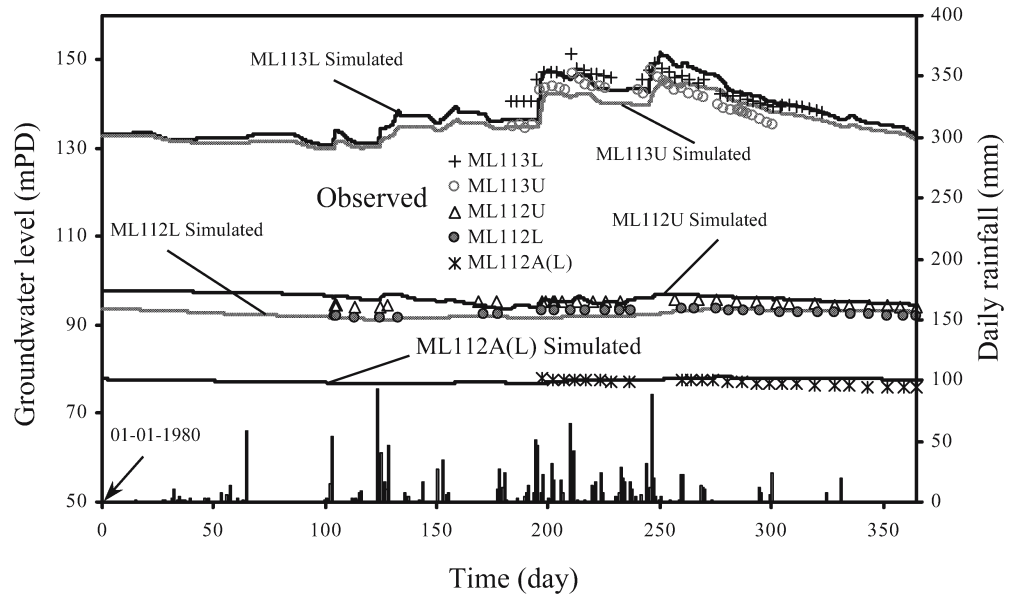
A special parameter R_u is introduced here to indicate the degree of reduction of hydraulic conductivity and storage capacity of the aquifers due to deep foundations in the urbanized areas. R_u is defined as the ratio of the aquifer parameter of the natural soil and that of the ur-

Table 1 Parameters used in the numerical model

Layer	R_u	K_s (10^{-5} m/s)	S_s	θ_s (%)	θ_r (%)	a_w (kPa^{-1})	n_w	a_k	n_k
Colluvium	20.1*	5.8*	0.009*	40	16	0.5	2.3	0.1	3.0
CDR	16.7*	0.03*	0.002*	37	17	1.0	2.8		
HKZ	13.6*	3.4*	0.00002*	20*	7*	0.8*	2.5*		
Bedrock	n/a	0.0005	0.000001	10	2	1.4	3.0		
Fill materials	n/a	0.008	0.004	35	13	1.0	2.8		
Marine mud	n/a	0.0001	0.01	n/a	n/a	n/a	n/a	n/a	n/a

Note: * stands for parameter values calibrated. Marine mud is always saturated so that only K_s and S_s are required; n/a stands for “not applicable”

Fig. 4 Observed and simulated groundwater levels in 1980 at piezometer groups of ML113 and ML112



banized soil, including both the soil and foundation materials:

$$R_u = \frac{K_s(h)}{K_u(h)} = \frac{S_s(h)}{S_u(h)} \quad (6)$$

where the subscript u stands for the parameters in the urbanized area which include both the soil and foundation materials. For simplicity, it is assumed that only the two key parameters, hydraulic conductivity K_s and specific storage S_s , are affected by foundation materials and that R_u is the same for K and S . It is expected that R_u will differ for different model layers because the disturbance of the foundation materials changes with depth. The degree of urbanization changes in the same layer as well, but for simplicity, only a single value is given to the soil in the urbanized area of the same layer.

The unsaturated hydraulic properties of colluvium and CDR (completely decomposed rock) in other parts of Hong Kong with similar geological conditions have been studied (Ng 1988) and are used in the model. Unsaturated hydraulic properties of bedrock and fill materials in the reclaimed land are quoted from the literature. The model is not sensitive to these parameters because the bedrock and fill materials in the reclaimed land are almost entirely saturated. All the parameters used in our model are listed in Table 1.

Discussion of the Numerical Results

Case 1: Simulation with Deep Foundations, Reclamation, and HKZ

In the first simulation the effects of deep foundations, land reclamation, and HKZ (high hydraulic conductivity zone) are all considered in the model. This simulation also serves a base for discussion and comparison. Some key parameters are calibrated by comparing the simulated water level with the observed one. Although no attempt has been made to calibrate the model rigorously, Fig. 4 shows that the match between the simulated and observed water level is reasonable. The sensitive and insensitive responses to rainfall in ML113 and ML112 are reproduced. This shows that the model can simulate the dynamic process of the water level in response to rainfall.

The values of parameter R_u calibrated for the three units overlying bedrock are shown in Table 1. Due to the deep foundations, the overall hydraulic conductivities are reduced by 14 to 20 times. The reduction in hydraulic conductivity decreases as the depth of the soils increases. This is reasonable because the disturbance of foundation construction is more significant in the shallow soils such as colluvium and CDR. The deep HKZ at the rockhead is disturbed mainly by various deep piles of high buildings.

Fig. 5 Simulated groundwater flow in the hillside on July 1, 1980, considering the effects of reclamation and urbanization with (a) and without HKZ(b)

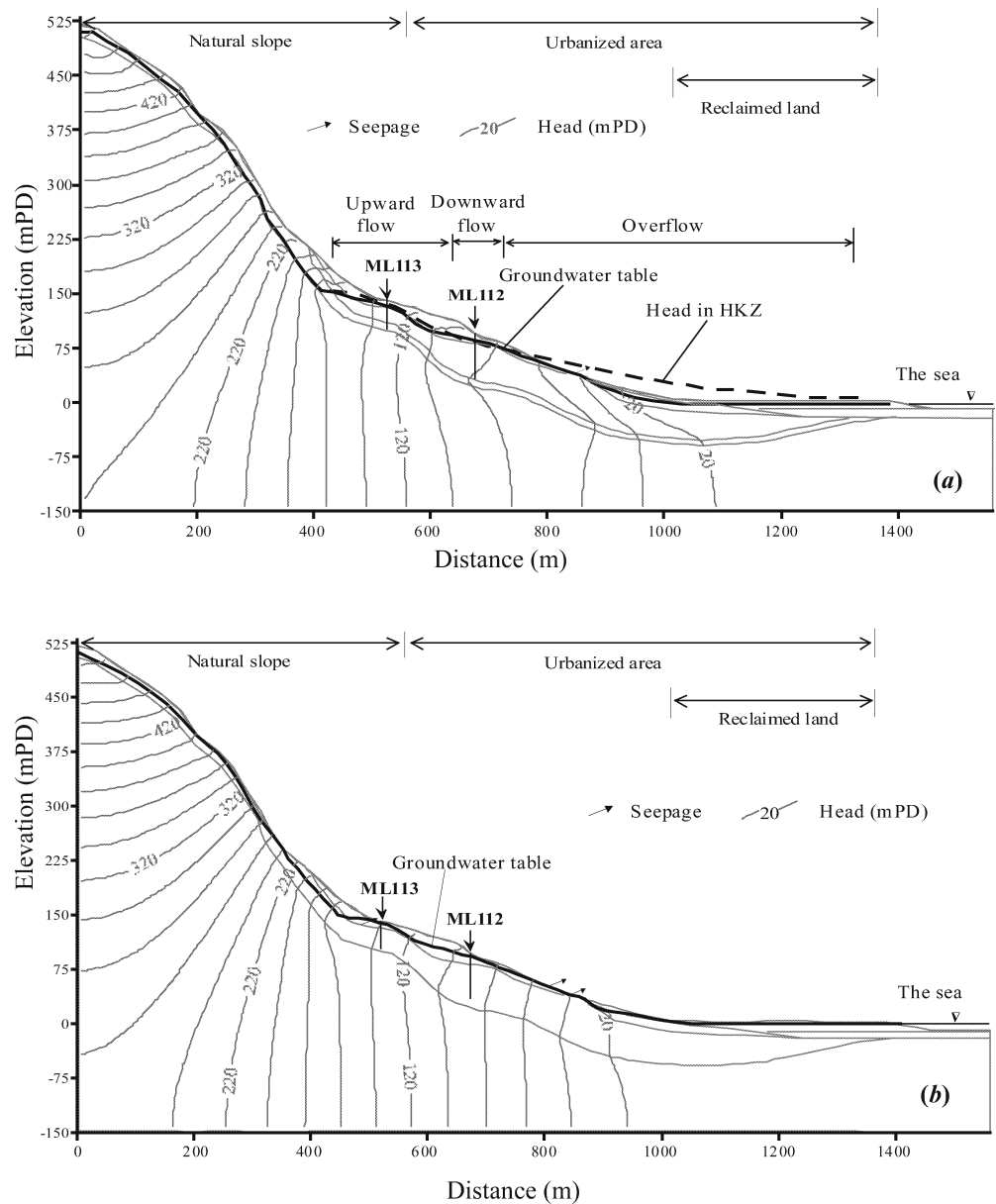


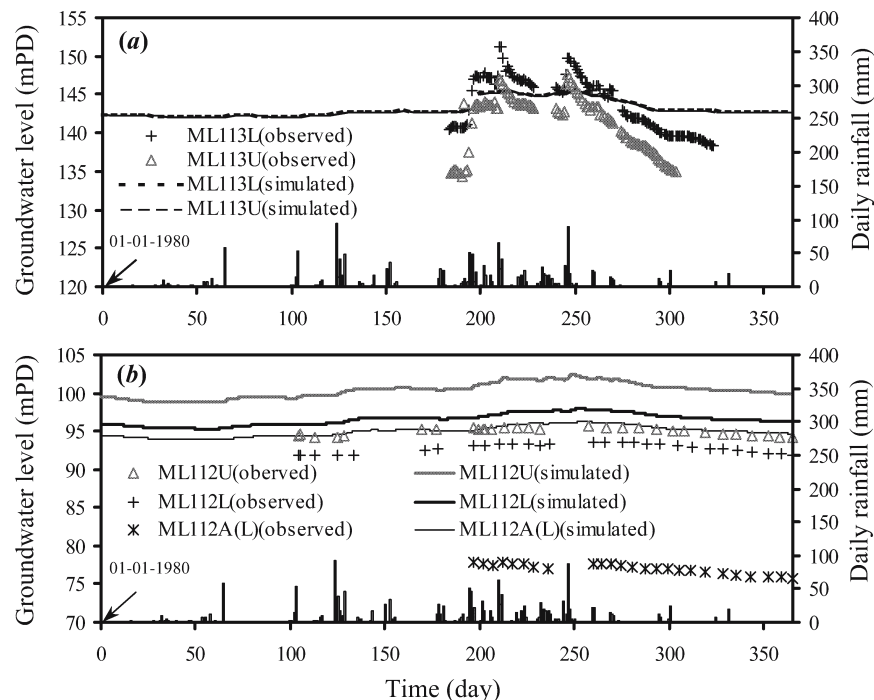
Figure 5a shows the simulated overall flow condition in the hillslope on July 1, 1980. The following terms are defined. Upward flow: water level in the HKZ is greater than that in the shallow unconfined aquifers, but less than the ground elevation; Overflow: hydraulic head in the HKZ is greater than the ground elevation; Downward flow: water level in the HKZ is lower than that in the shallow unconfined aquifers. As shown in Fig. 5a, upward flow occurs at the upper end of the cross-section, and downward flow occurs in the middle of the slope where the ground surface becomes flatter and HKZ surface becomes steeper. Overflow occurs in the lower parts of the section where the HKZ bends upwards and the shallow soil becomes thin. This overall flow pattern matches well with the observed groundwater zones discussed earlier. Seepage zones occur where unconfined groundwater seeps out of the ground surface.

Case 2: Simulation with Deep Foundations and Reclamation but no HKZ

Upward flow can be generated at the toe of a slope (Hubbert 1940). In the study area, at the junction of the natural slope and urbanized area, the ground surface changes from steep to fairly gentle slopes. Thus, it is possible that the upward flow at the transitional area could be caused by the change in topography, instead of the HKZ (high hydraulic conductivity zone). To test this possibility, the model was run without the HKZ. The HKZ material is replaced by CDR of low hydraulic conductivity.

Figure 5b shows the simulated flow pattern without HKZ on July 1, 1980. The aquifer system becomes an unconfined system. Seepages occur in the Mid-Levels, but all the observed key features in Fig. 5a, such as up-

Fig. 6 Comparison of observed and simulated water levels at ML113 (a) and ML112 (b) in 1980. The model has no HKZ and the hydraulic conductivity of the CDR (completely decomposed rock) is 1×10^{-6} m/s



ward and downward flow disappear. The simulated water levels of tips ML113U and ML113L, which are now both in CDR (completely decomposed rock) of $K=3 \times 10^{-7}$ m/s, are almost the same and not sensitive to rainfall (not shown here), which is distinctly different from the simulated results produced by including the HKZ and the observed results. The match between the simulated and the observed water levels at tips ML112U, ML112L, ML112A(L) is also poor.

Although it is believed that K for CDR should be fairly low because CDR behaves as a confining unit for the underlying HKZ, local engineers may argue that the K value for the CDR used here is too small. Thus, the model was run again after setting the K of the CDR materials to 1×10^{-6} m/s, a value recommended by the Mid-Levels study and later accepted as typical for CDR in Hong Kong. The simulated groundwater level at ML112 and ML113 is shown in Fig. 6. The fluctuation of water level at ML113 increased, but is still insignificant compared to the observed fluctuation. The simulated water levels at ML112 are much higher than the observed ones.

Obviously, simulations without a HKZ cannot reproduce the observed features of groundwater levels. This demonstrates that the HKZ is essential and should be included in the aquifer system in the hillside of the model area.

Case 3: Simulation Without Reclamation and Deep Foundations—Flow in Natural State

To investigate the change of groundwater regime before and after urbanization and land reclamation in the study area, the natural state of groundwater flow was simulated. This is done by letting R_u of all the layers be 1.0, re-

moving the fill material, and using the original coast line. The same rainfall as 1980 is applied and the rainfall infiltration rate of 50% is used over the entire ground surface.

The natural groundwater flow in the hillside is shown in Fig. 7. The groundwater level is much lower than that from the initial simulation that includes the fill materials and deep foundations (Fig. 5a). In the natural state, all the piezometer tips of ML112 and ML113 are unsaturated, and the seepage and overflow zone occur only near the coastline, which is very similar to the situation observed in 1888. As can be seen by comparing Figs. 5a with 7, after land reclamation and urbanization, the overflow area is increased and moves uphill; the downward flow area is decreased; and an upward flow area is generated at the transition between the natural and urbanized slopes. This is because the flow to the sea is reduced and groundwater is forced to seep out due to land reclamation which increases the flow path to the sea and deep foundations which reduces the overall hydraulic conductivity of the soil.

Case 4: Simulation to Compare the Impacts of Deep Foundations with Reclamation

To understand how the flow is impacted by reclamation and then by deep foundations, the model was first run by considering land reclamation only. This was done by setting R_u in all the layers to 1.0. Other settings remain the same as for Case 1.

Groundwater flow patterns with only the impact of reclamation are presented in Fig. 8. Compared to Fig. 7, it can be seen that reclamation increases remarkably the hydraulic head in the HKZ (high hydraulic conductivity

Fig. 7 Simulated groundwater flow in the hillside on July 1, 1980 in the natural state (without the impact of reclamation and urbanization), assuming rainfall equal that of 1980

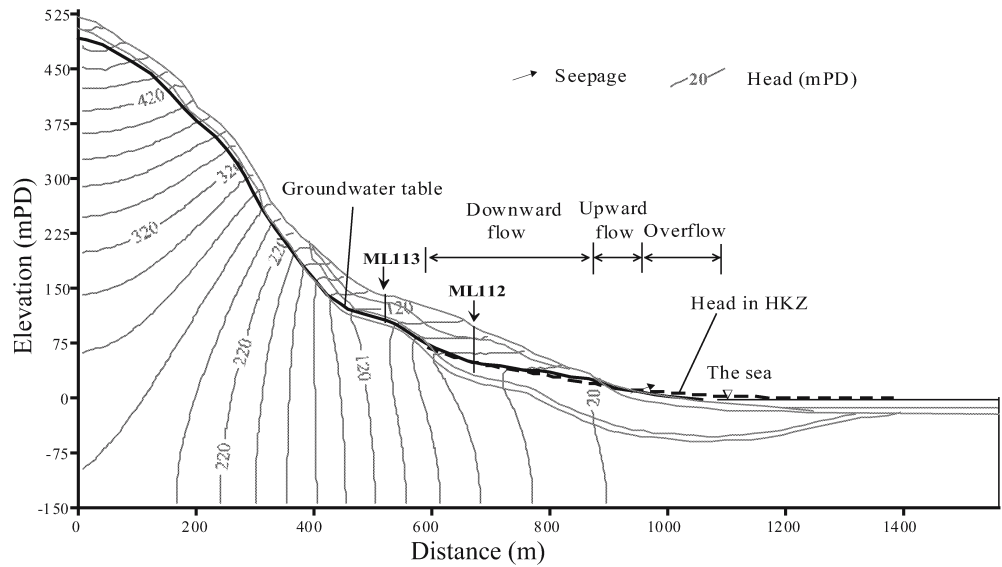


Fig. 8 Simulated groundwater flow in the hillside without urbanization on July 1, 1980 in response to reclamation only, assuming rainfall equal to that of 1980

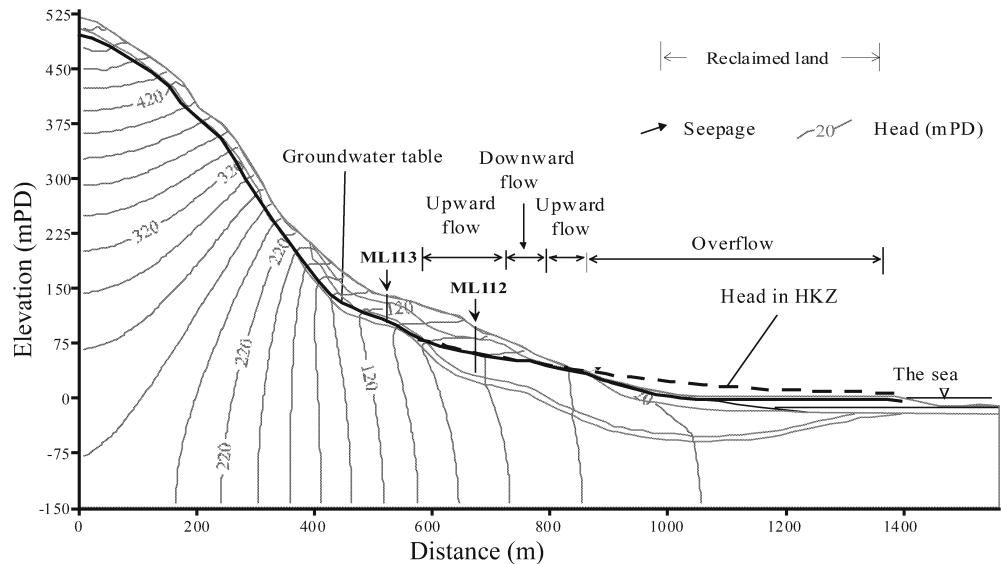


Table 2 Change of water levels at the tips of ML112 (a) and ML113 (b) on July 1 1980 due to land reclamation and deep foundations, assuming rainfall equal to that of 1980

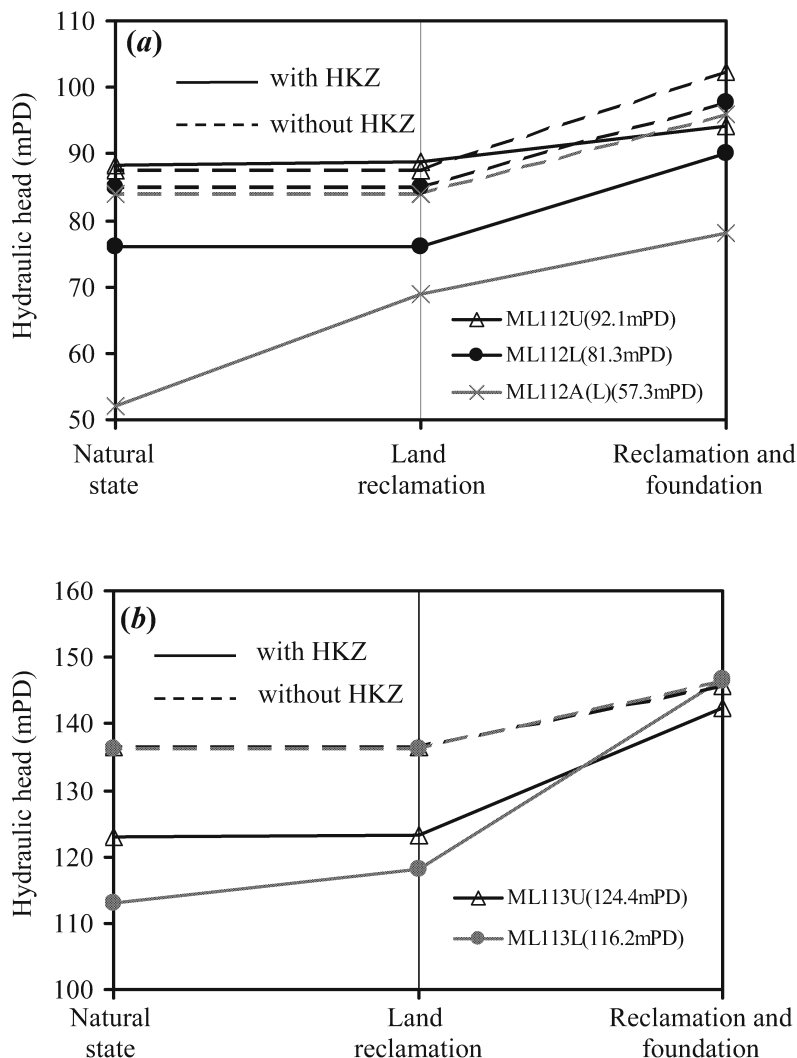
Piezometer	Tip elevation (mPD)	Hydraulic head (m) with HKZ			Hydraulic head (m) without HKZ		
		Natural state	Land reclamation	Reclamation and urbanization	Natural state	Land reclamation	Reclamation and urbanization
ML113U	124.4	123.0*	123.3*	142.3	136.4	136.5	146.5
ML113L	116.2	113.0*	118.1	146.7	136.3	136.3	146.5
ML112U	92.1	88.2*	88.7*	94.1	87.6*	87.7*	102.4
ML112L	81.3	76.0*	75.9*	90.3	85.0	85.1	97.7
ML112A(L)	57.3	51.9*	69.0	78.1	83.9	84.0	95.8

Note: * indicates that the tip is in unsaturated zone

zone) and unconfined shallow aquifers: overflow and upward flows are generated in the Mid-levels area and a larger seepage zone is produced. However, without HKZ, the effect of reclamation is much less significant (not shown here). This indicates that HKZ enhances the impact of reclamation and urbanization on groundwater flow.

Further changes in the flow system after deep foundations are considered can be observed by comparing Fig. 8 with Fig. 5, which includes both reclamation and foundation (Case 1). To understand better how the water level is affected by reclamation and then by deep found-

Fig. 9 Change of water levels at the tips of ML112 (a) and ML113 (b) on July 1, 1980 due to land reclamation and due to insertion of deep foundations, assuming rainfall equal to that of 1980



dations, simulated water levels at ML112 and ML113 on July 1, 1980 are presented in Table 2 and Fig. 9.

When there is no HKZ (see broken lines in Fig. 9), the water levels at all the piezometer tips in the Mid-Levels do not change much with reclamation, but do change appreciably when deep foundations are added. This is probably because the hillslope without a HKZ is an unconfined system, so the piezometers located far from the coast are not much affected by coastal reclamation (Jiao 2000). Deep foundations still have a considerable impact on the system because they reduce the soil hydraulic conductivity in the entire urbanized area.

When the HKZ is included, the impact of reclamation and urbanization on water levels depends on the tip locations. The water levels in the shallow soil, or the unconfined aquifer (tips ML112U, ML112L in Fig. 9a and tip ML113U in Fig. 9b), do not change much with reclamation, but the deep tips, or the tips in the HKZ (ML112A(L) in Fig. 9a and ML113L in Fig. 9b) are sensitive to reclamation. All the tips are sensitive to urbanization except tip ML112U that is very shallow.

In summary, urbanization has a greater impact on water levels than reclamation. This is probably because reclamation mainly affects the water levels near the coastline whereas urbanization leads to hydraulic conductivity reduction in the entire urbanized area. Overall, urbanization and reclamation have a larger impact on the flow system when a HKZ is present.

Summary and Conclusions

This paper has investigated the effect of land reclamation and deep foundations on groundwater flow system in a coastal hillslope area on Hong Kong Island. Uphill movement of seepage zones, flooded basement and piezometric response demonstrate that there is an upward flow zone at the transitional area between the natural slope and the developed area. Based on piezometric response, the artesian groundwater observed in the lower parts of the study area and the hydraulic conductivity observed in other igneous areas of Hong Kong, a confined

HKZ (high hydraulic conductivity zone) is believed to exist along the rockhead in the study area.

Deep foundations in urbanized areas also appear to retard groundwater flow such that some of the groundwater is forced to flow upward at the transitional area between the natural slope and the developed areas. Part of the groundwater still flows downhill, largely through the HKZ, but submarine discharge is again retarded by the fill materials in the reclaimed area. Based on natural factors, such as local topography and the shape of the bedrock, and human intervention, such as construction of deep foundations and land reclamation, the groundwater flow regime can be divided into four zones: downward flow zone in the natural slope, upward flow zone at the transitional area, downward flow zone in the middle of the hill, and upward flow zone again along the coast. The exact location of these zones will change with rainfall and future human activities. For example, in wet years, the upward flow zone along the coast may move uphill and the downward flow zone in the middle of the hill may shrink or even disappear.

A two-dimensional, unsaturated-saturated finite element flow model has been developed to investigate the mechanisms responsible for changes in the flow system and the model is calibrated against the water level observed in 1980. To reproduce the observed upward flow on the hillside, the model has to include two important features: a HKZ and a reduction in hydraulic conductivity of 14–20 times in the urbanized area. Numerical simulations for different cases show that both land reclamation along the coastline and deep foundation have modified the flow system. The construction of deep building foundations has the largest impact because it reduces the overall conductivity of the developed area by replacing the natural soil with much less permeable foundations and other construction materials. The HKZ is an enhancement factor for modification of the flow system by urbanization activities since blocking off the groundwater flow in such a zone will build up the water level in a large part of the hillside.

The study presented here is of not only theoretical significance but also practical implications. It is believed that a better understanding of these effects is conducive to the planning, design and maintaining sustainable development in coastal urbanized areas. For example, land reclamation and foundation design should be formulated in such a way that the regional groundwater flow is least modified. It should be pointed out that some model parameters such as infiltration rate and hydraulic conductivities are uncertain and these will impact the modeling results. However, the general conclusions about the change of the groundwater pattern due to reclamation and foundations are reasonable. Field hydrogeological information and more comprehensive modeling studies are needed before more robust conclusions can be made.

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