

Analysis of urbanisation-induced land subsidence in Shanghai

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Abstract Since 1980, land subsidence has accelerated and groundwater levels have decreased in the centre of Shanghai, although the net withdrawn volume of groundwater has not increased. Theoretical analysis of the monitored data shows that the decrease in the groundwater level is the primary reason for the observed land subsidence. Meanwhile, the net withdrawn volume of groundwater in the urban centre of Shanghai has not increased during this period. Many underground structures have been constructed in the multi-aquifer-aquitard system of Shanghai since 1980. This paper discusses the factors related to the development of land subsidence during the process of urbanisation in Shanghai during the past 30 years. These factors include additional load during and after structure construction, the cut-off and/or partial cut-off effect of underground structures in aquifers, the decrease in the groundwater level due to leakage of underground structures and the reduction in recharge of groundwater from the surroundings.

Keywords Land subsidence · Groundwater withdrawal · Urban construction · Soft deposit · Cut-off of groundwater

1 Introduction

Urbanisation impacts the environment by creating air, water and noise pollution and by deteriorating the geological environment by inducing geohazards, for example, land

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subsidence and groundwater contamination. In Shanghai, the groundwater pumping volume as well as the land subsidence has been officially recorded since 1921 (Chai et al. 2004; Xu et al. 2008). Until 2009, the average cumulative subsidence in urban areas was 1.97 m (SMBPLR 2001–2009). Groundwater pumping was considered to be the primary reason for land subsidence in Shanghai. From 1921 to 1965, the pumped volume of groundwater increased annually, causing land subsidence and changes to the geological environment of Shanghai. Since 1966, some measures have been adopted to minimise land subsidence to less than the allowable value of 5 mm/year, for example, decreasing the groundwater withdrawn volume, adjusting the groundwater withdrawn layer in the aquifers and conducting artificial recharging. During the period of 1972–1989, the average subsidence rate (v_{s1}) was 3.6 mm/year, which was within the allowable range. However, the average subsidence rate from 1990 to 1995 (v_{s2}) was 9.97 mm/year, which is nearly 2 times greater than v_{s1} . The average subsidence rate from 1996 to 2009 (v_{s3}) was 12.09 mm, which is 3 times greater than v_{s1} and is much greater than the allowable value. In other words, during the 1990s, land subsidence accelerated although the net withdrawn volume of groundwater, which is equal to the difference between groundwater withdrawn volume and recharged volume, did not increase.

At the same time, a large number of municipal facilities, for example, gas pipelines, water supply, sewerage water, electricity, underground rail tunnels, and high-rise buildings, have been constructed in the urban centre of Shanghai. Some researchers indicated that urban construction is one of the causes of land subsidence in Shanghai (e.g., Gong et al. 2005; Zhang and Wei 2005; Xu et al. 2009). It has been reported that the ratio of subsidence induced by urban construction to the total amount of land subsidence is about 30 % (Gong et al. 2005). However, the mechanism by which urban construction affects the acceleration of land subsidence in Shanghai has not been well addressed.

The objective of this paper is to analyse factors related to the development of land subsidence accompanying urbanisation of Shanghai. For this purpose, the engineering geology and hydrology of Shanghai is first introduced. Then, the relation of geological and hydrological conditions to foundation construction is discussed. The relation between the groundwater withdrawn volume and land subsidence is also discussed. Finally, a quantitative relationship among the floor area of buildings, the mileage of the rail track transportation system and the cumulative subsidence is analysed.

2 Engineering geology and hydrogeology in Shanghai

Shanghai is located on the south bank of the estuary of the Yangtze River. For the most part, the land in Shanghai is a soft deltaic deposit with some isolated outcrops of bedrock. The bedrock outcrops are scattered in isolated mounds with a total area of about 2.5 km². Most of the bedrock is buried under quaternary and tertiary sediments at a depth of over 300 m. The quaternary deposit in Shanghai primarily consists of a phreatic aquifer group (Aq0) and five artesian aquifers (AqI–AqV) that are separated by six aquitards (AdI–AdVI). The phreatic aquifer group consists of a phreatic aquifer (Aq01) and a low-pressure artesian aquifer (Aq02). The details of the forming era and sedimentary environment of each stratum can be found in our earlier work (Xu et al. 2009).

The buried depths of the subsoil strata, which are related to geotechnical engineering practices, reach 100 m (Shen et al. 2010; Tan and Wei 2011). According to the physical properties and the forming era, from top to bottom, the soft deposit can be divided into nine engineering geological layers including a topsoil layer, a first sand layer, a first soft clay

layer, a first hard soil layer, a second soft clay layer, a second hard soil layer, a second sand layer, a third soft clay layer and a third sand layer (Xu et al. 2009; Shen and Xu 2011). Figure 1 shows the properties of the subsoil within 100 m in Shanghai.

Figure 2 shows the relationship among engineering geology, hydrogeology and bearing strata of building foundations and municipal facilities. Many municipal facilities were built directly in the topsoil layer or in a treated topsoil layer. Middle-high-rise buildings (20–30 m) often adopt the second stiff clay layer or the second sand layer as the bearing stratum for their pile foundations, and high-rise buildings (over 30 m) generally adopt the second sand layer as the bearing strata for their pile foundations. Super-high-rise buildings (over 100 m) and ultra-high buildings (over 200 m) usually select the third sand layer as the bearing strata for pile foundations. Other underground facilities (e.g., subway tunnels) usually adopt the first and second soft clay and AqI as the bearing strata (SGEAE 2002). The buried depth of the tunnel under the Huangpu River is 30–40 m, which includes AqI. Besides the building foundations, there are many diaphragm walls that are used as retaining structures for excavations constructed in the deposit at a depth of 30–50 m. All of these underground facilities will change the hydrogeological conditions in Shanghai. These effects will be discussed later in this paper.

3 Land subsidence, groundwater withdrawn volume and urban construction in Shanghai

Figure 3 shows the relationship between cumulative subsidence and net withdrawn volume of groundwater in Shanghai. There is a correlation between the cumulative subsidence and the net withdrawn volume until 1980. Before that time, increases in net withdrawn volume accompanied land subsidence increases. However, since 1980, there has been a discrepancy between subsidence and the net withdrawn volume. Although the net withdrawn volume decreased, subsidence accelerated. To further investigate the crucial factors

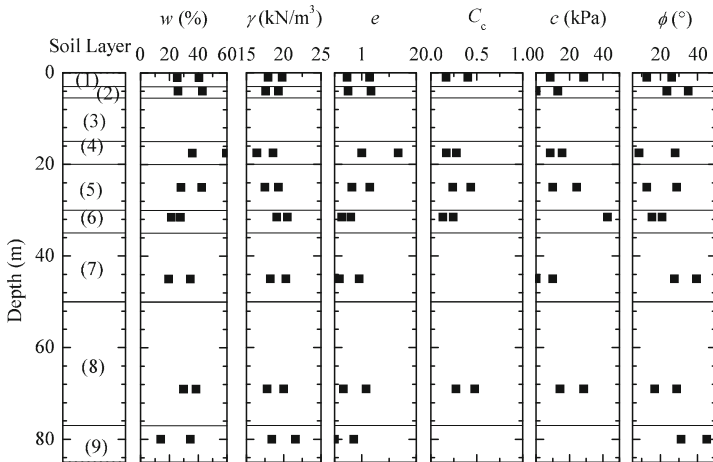


Fig. 1 Properties of the subsoil within 100 m in Shanghai (data from SGEAE 2002). *Note:* w = water content, γ = unit weight, e = void ratio, C_c = compression index, c = cohesion force, ϕ = internal friction angle, 1 natural ground layer, 2 first sand layer, 3 first stiff clay layer, 4 first soft clay layer, 5 second soft clay layer, 6 second stiff clay layer, 7 second sand layer, 8 third soft clay layer, 9 third sand layer

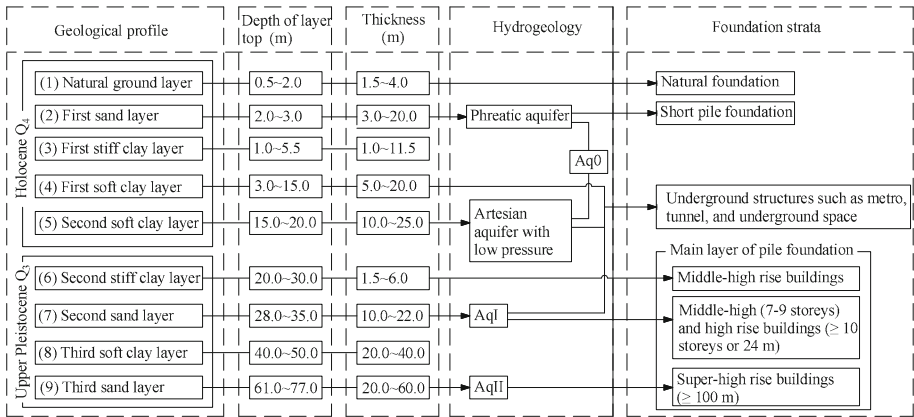
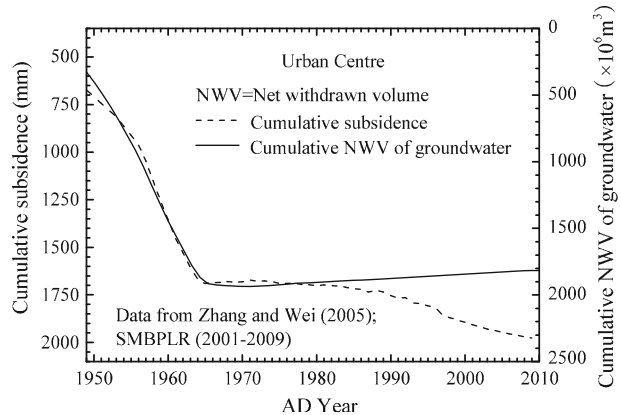


Fig. 2 Relationship among engineering geology, hydrogeology and foundation strata in Shanghai

Fig. 3 Relationship between cumulative subsidence and net withdrawn volume of groundwater



affecting subsidence, the cumulative subsidence versus the cumulative net withdrawn volume are plotted in Fig. 4. The cumulative subsidence increased with increases in the cumulative net withdrawn volume of groundwater until 1980. However, since 1981, the cumulative subsidence continued to increase even though the net withdrawn volume decreased, which indicates that net withdrawn volume is not a crucial factor for land subsidence. Once the net withdrawn volume exceeded a given value, limitation of the withdrawn volume had no effect on subsidence in the urban centre. The mechanism of the phenomenon that settlement increases whereas net withdrawn volume decreases needs to be further investigated.

Figure 5 shows net withdrawn volume in the urban centre and the suburban region of Shanghai. Before 1965, the net withdrawn volume in the urban centre was larger than that in the suburban region. After 1965, the net withdrawn volume in the suburban region was larger than that in the urban centre. In the late 1970s, groundwater was artificially recharged in the urban centre, which caused the net withdrawn volume decrease in the urban centre (see Fig. 4).

Figure 6 shows groundwater level of each aquifer in Shanghai since 1980. Figure 7 shows the relationship between cumulative subsidence and the groundwater level in each aquifer since 1980. There is a strong correlation between land subsidence and the groundwater level

Fig. 4 Comparison of cumulative land subsidence and net withdrawn volume of groundwater (adapted from Xu et al. 2009)

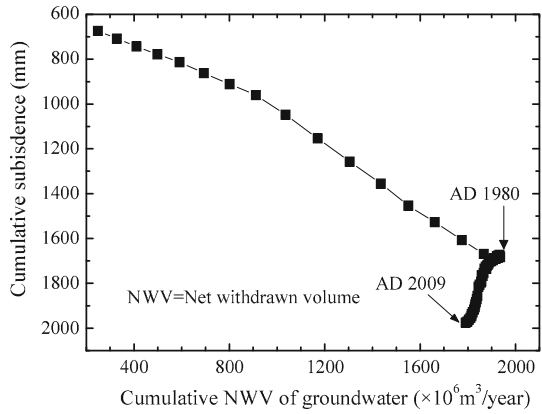


Fig. 5 Net withdrawn volume in urban centre and suburban region

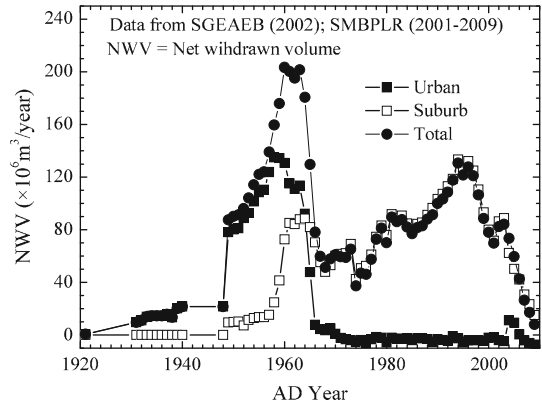
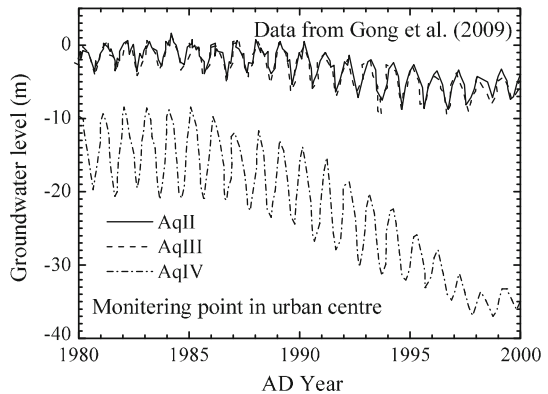


Fig. 6 Groundwater level of each aquifer in Shanghai



of each aquifer. The high coefficients of correlation ($R^2 = 0.95, 0.95, 0.99$ for AqII and AqIII, and AqIV, respectively) show that the reduction in the groundwater level is most likely a crucial factors related to land subsidence. As a result, it is necessary to reveal the mechanisms of the continuous reduction in the groundwater level in the urban centre. One of the possible reasons is the cut-off effect due to the existence of underground structures in aquifers, which is similar to what occurred in Hong Kong (GCO 1982; Jiao et al. 2008).

Fig. 7 Comparison of cumulative subsidence and groundwater level in each aquifer since 1980

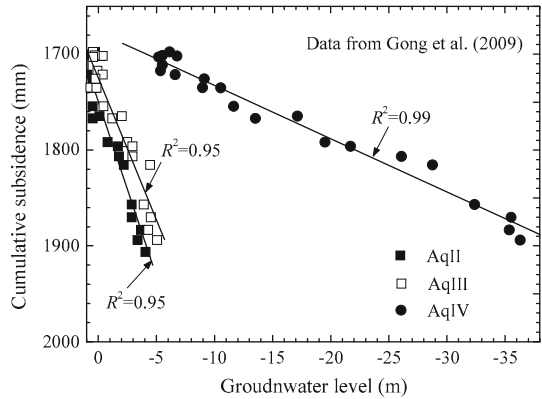
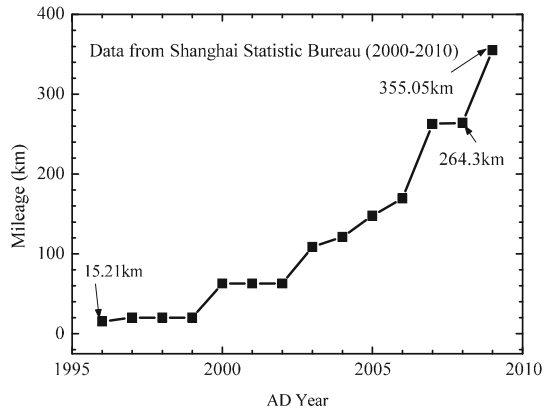


Fig. 8 Variation of rail track mileage in Shanghai



In fact, urbanisation and the development of many underground structures (e.g., underground pipelines, rail tunnels and building foundations) have occurred in the multi-aquifer-aquitard system (MAAS) of Shanghai since the 1980s. Regarding urbanisation-induced subsidence, many researchers initially focused on land subsidence due to engineering construction (Cui et al. 2010; Gong et al. 2005; Tang et al. 2008). Figure 8 shows the variations in the mileage of the rail transportation system in Shanghai. The mileage of rail track started at 15.21 km in 1996 and reached 355.05 km in 2009. Most of the rail system goes through underground tunnels. Figure 9 shows the variation of the floor area of high-rise buildings since 1980 in Shanghai. The floor area of buildings increased annually.

Figure 10 shows the variation of the floor area and the cumulative subsidence for each year since 1966. Since 1980, the annual rate of subsidence in the three periods (see Fig. 10) was 3.84, 9.97 and 12.09 mm/year, corresponding to an increasing floor area of the buildings higher than 8 storeys of 0.58×10^6 , 2.30×10^6 and 13.17×10^6 m²/year, respectively. To investigate the relationship among floor area, mileage of rail track and cumulative subsidence, regression analyses were conducted. Figure 11 shows the regression analysis between floor area and cumulative subsidence. As seen in Fig. 11, there is a strong correlation between floor area and cumulative subsidence. This relation can be fitted by an exponential function with a very high coefficient of correlation ($R^2 = 0.993$). Figure 12 illustrates the relationship between the mileage of rail track and the cumulative

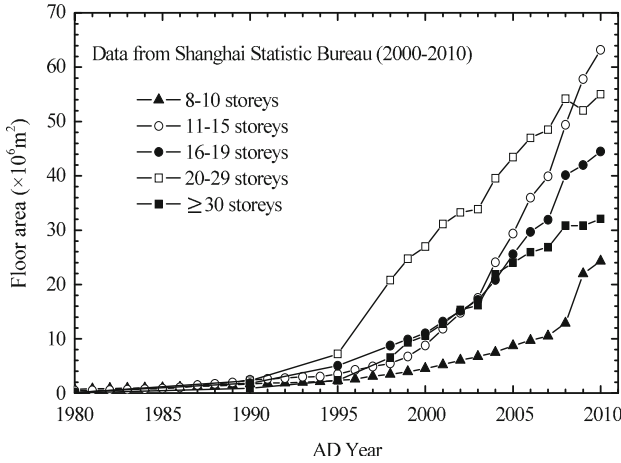


Fig. 9 Variation of building areas in Shanghai since 1980

Fig. 10 Relationship between floor area and cumulative subsidence

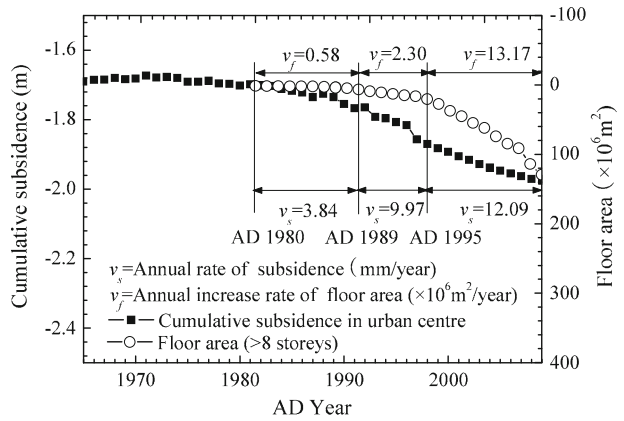
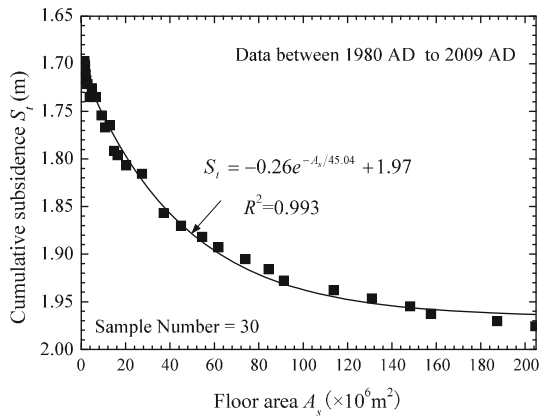
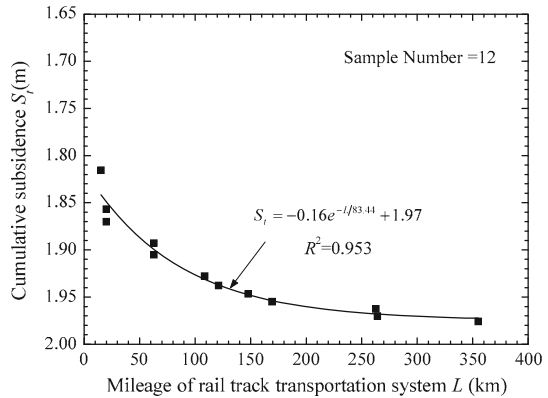


Fig. 11 Regression analysis of floor area and cumulative subsidence



subsidence. The relationship is similar to that between the floor area and the cumulative subsidence. The coefficient of correlation is 0.953, indicating that the rail track transportation system and the floor area have contributed significantly to the acceleration of land

Fig. 12 Regression analysis of rail track mileage and the cumulative subsidence



subsidence in Shanghai since 1980. Since the first subway tunnel was officially constructed in 1990, there is no correlation between mileage of rail and cumulative subsidence before 1980. According to statistics, increasing rate of floor area of all of the buildings in urban centre of Shanghai is equal to 1.60×10^6 , 1.82×10^6 and 7.82×10^6 m^2/year in 1960s, 1970s and 1980s, respectively (SCHEB 2005). The construction of high-rise building in Shanghai was started at the end of 1970s and was developed rapidly during 1980s. It is obvious that such small-scale of urban construction before 1980 has no significant effect to lead land subsidence. Moreover, there is no available data of floor area before 1980, and we considered that there were no correlations between floor area and cumulative subsidence before 1980. Thus, we concluded that the construction of infrastructure (e.g., building foundations and rail tunnels) has contributed to land subsidence in Shanghai since 1980.

4 Discussion of factors on subsidence

Table 1 tabulates the influence of factors resulting in land subsidence due to urbanisation processes in Shanghai. As shown in Table 1, the factors, which might influence the acceleration of land subsidence since 1980 fall into the following three categories: (1) additional loads in subsoil, including building loads and dynamic loads, (2) construction of underground structures, including construction of tunnels and foundation pits, (3) long-term reductions in groundwater levels, which may be caused by leakages of tunnel linings, cut-off of groundwater flow due to the existence of underground structures in aquifers and reduced replenishment of groundwater from suburban regions. The mechanisms of subsidence will be discussed in detail in the following sections.

4.1 Additional load

Until recently, most researchers attributed urbanisation-induced land subsidence to the additional building loads acting on the subsoil (Jie et al. 2007; Tang et al. 2008; Cui et al. 2010). Since 1980, more than one thousand high-rise buildings have been constructed in the urban area of Shanghai. These buildings use pile foundations. For AqI, the depth of the piles reaches 45 m, and for AqII, the length of piles is from 60 to 90 m. Tang et al. (2008) conducted an analysis of the influence of additional stress in subsoil resulting from the

Table 1 Influence factors resulting in land subsidence with urbanisation of Shanghai

Category	Reason type
Additional load	Building load
	Dynamic load
Underground structures construction	Construction of foundation pit
	Pit excavation
	Pit dewatering
Long-term drawdown of groundwater level	Construction of tunnel
	Tunnel leakage
	Reduction in groundwater replenishment from surrounding
	Groundwater withdrawal in suburban region
	Cut-off effect on groundwater seepage due to underground structures

high-rise buildings on land subsidence based on a model test. Jie et al. (2007) found that subsidence increases with an increase in construction scale and speed. Subsidence increased with increasing building density and volumetric fraction. The soft deposits in Shanghai are typically soft soil with high compressibility and rheological behaviour (Yin and Graham 1996; Yin et al. 2011). Therefore, the primary consolidation will last a long time, and secondary consolidation settlements will be large under the additional stress.

Dynamic loads, due to pile driving and traffic loading, also affect land subsidence. Ground vibration caused by pile driving will make the soil deform. Jongmans (1996) considered that the radius of influence due to pile driving was about 50 m. Cyclic traffic loading will result in cyclic cumulative soil deformations. Ling et al. (2002) estimated that the residual settlement of a road at the outer ring road intersection in Shanghai due to traffic loading was 50 mm.

4.2 Construction of underground structures

Construction of underground structures (e.g., tunnels and foundation pits) will disturb the subsoil and cause deformations of the surrounding ground. Underground rail tunnels are also associated with land subsidence. Long-term ground movement can have a significant effect on the behaviour of tunnel linings. Ground movement induced by tunnelling can continue for many years. The annual differential settlement associated with the tunnel of Metro Line No. 1 was about 30 mm, and the maximum cumulative subsidence reached 300 mm after 15 years (SMRM 2007; Wu et al. 2011).

In recent years, a large amount of underground construction has been conducted in the urban centre of Shanghai (e.g., Peng et al. 2011; Tan and Li 2011). Foundation pit excavation, with a maximum depth of 40 m, has also affected land subsidence in Shanghai (Peng et al. 2011). With the development of underground spaces, both the depth and size of excavations have increased. The influence range of deep excavation to land subsidence can be 15 times the depth of excavation. Most of the excavations in Shanghai are dry excavations, that is, the groundwater level is lowered with the excavated surface with well points or deep wells. With the withdrawal of groundwater, a groundwater head depression cone will form around the pit. According to engineering practices, the influence range of

foundation pit dewatering is 300–800 m (Shen and Xu 2011). The settlement is 5–15 mm when the drawdown of groundwater level is about 3.5 m (Huang and Gao 2005).

4.3 Long-term groundwater level reductions

As shown in Fig. 3, the net withdrawn volume of groundwater in the urban centre has decreased since 1980. Therefore, the net withdrawn volume of groundwater is not the most significant factor related to the reduction in the groundwater level. On the other hand, as presented in Fig. 5, the reduction in the groundwater level is still strongly correlated with land subsidence in Shanghai. The following factors, which are related to the process of urbanisation, may explain this phenomena: (1) an increase in groundwater withdrawal in suburban areas; (2) the cut-off effect on groundwater replenishment to the urban centre from the surroundings due to the existence of underground structures in aquifers and (3) leakage of groundwater into rail tunnels and into the basements of buildings.

Generally, groundwater flows from a position with a high potential to a position with a low potential. When groundwater in an aquifer is pumped out, the groundwater level depresses around the pumping well. When groundwater was pumped into the urban centre, groundwater could be replenished from the suburban region. As shown in Fig. 4, the ratio of the net withdrawn volume for the urban area to the suburban area was 8:1 in 1949, 1:0.98 in 1964 and 1:70.7 in 1970. The suburban region has become the main source region for groundwater withdrawal since the 1970s. Thus, groundwater cannot be replenished sufficiently in the urban centre due to the increased volume of groundwater withdrawal in the suburban area.

Another reason for the reduction in recharged groundwater volume is the cut-off effect on groundwater seepage due to the existence of underground structures in aquifers. Infrastructures in aquifers can be considered as retaining walls, which cut off groundwater flow. The groundwater head of an aquifer changes from a hydrostatic pressure condition to a transient downward flow condition due to the existence of underground structures. The head of the groundwater ascends at the side of the underground structure with a higher potential, and the head of the groundwater depresses at the side with a lower potential when the steady flow condition is changed by the constructed underground structures (Xu et al. 2009). Therefore, groundwater flow routines change. Thus, underground structures will cut off the flow of groundwater and change the flow velocity and flow direction, which causes continuous reductions in groundwater levels in the AqI and AqII layers in the urban centre of Shanghai.

Some studies have suggested that the foundations became a type of barrier to groundwater movement (Johnson et al. 1984; Jiao et al. 2008). The existence of a large number of piles for high-rise buildings and tunnels in AqI and AqII reduced the groundwater recharge area from the surrounding areas to the urban centre. This change might have reduced the recharged groundwater volume from the surroundings and consequently might have caused the reduction in the groundwater head in the urban centre. The relationship between the rate of change of the groundwater head and the recharged groundwater volume can be expressed by Eq. 1 (Ketchum et al. 2000):

$$\frac{\partial h}{\partial t} = \frac{R(t)}{S_y} - \frac{Q(t)}{S_y A(t)} \quad (1)$$

where $\partial h/\partial t$ = rate of head change; $R(t)$ = recharge volume; $Q(t)$ = discharge flux; S_y = specific storage; and $A(t)$ = catchment area for the studied domain.

Integrating both sides with respect to time over an arbitrary temporal interval, T , yields a cumulative storage difference, which may be expressed as a uniform hydraulic head fluctuation, $\Delta h(T)$, over the full area of the catchment area:

$$\Delta h(T) = \frac{1}{S_y} \int_0^T R(t) \delta t - \frac{1}{S_y} \int_0^T \frac{Q(t)}{A(t)} \delta t \quad (2)$$

$$A(t) = A_0 - A_s(t) \quad (3)$$

where A_0 , $A(t)$ = catchment area at the beginning and at time t and $A_s(t)$ = obstructed area at the seepage route at time t .

In Eq. 2, a positive value of Δh indicates a net recharge, while a negative value of Δh indicates a recession. The existence of underground structures (i.e., pile foundations and underground tunnels) constructed since 1980 in AqI and AqII reduced the catchment area on the natural recharge route. As a result, from Eq. 2, it can be seen that the groundwater head decreased in the urban centre.

Xu (2010) performed a series of numerical analyses and concluded that the effect of the impervious wall on the groundwater flow is controlled by the depth of the impervious wall under the artesian aquifer, the width of the impervious wall and the distance of the impervious wall from drawdown border. Based on Xu (2010), the rate of subsidence in the urban area could be increased when the existence of underground structures was considered in the analysis. When the volume ratio of underground structures in AqII increases 10 %, subsidence increases about 32 %. However, when the volume ratio of underground structures in AqI and in the low-pressure aquifer increases by 10 %, the subsidence increases by only about 3 %.

The Shanghai underground railway system was constructed using the shield method, in which the lining consists of six segments. Field investigations show that soil and groundwater leak through joints, cracks and grouting holes in the lining segments (Mair 2008; Shin et al. 2002; Wu et al. 2011). The leaked volume is initially small, and tunnel deformation is usually neglected. As leaking increases, the original differential settlement may become aggravated and lead to further leakage of water and/or soils. The leaking of soil (and/or groundwater) causes long-term ground loss around tunnel. This results in the reduction in groundwater levels and ground movement around tunnel (Mair 2008). Wu et al. (2011) concluded that if the leakage in Shanghai tunnels was constant at a velocity of 0.1 l/m²/d and was distributed uniformly, then there would be a magnitude of settlement of 90 mm after 10 years.

5 Conclusions

Based on the analysis of factors influencing land subsidence due to urbanisation in Shanghai, the following conclusions can be drawn.

- (1) Land subsidence was not correlated with the withdrawn volume of groundwater after 1980, but land subsidence was still correlated with the reduction in the groundwater level.
- (2) Land subsidence in Shanghai is also correlated with urban construction. Regression analyses on the relationships among floor area, rail transportation system mileage and

- cumulative subsidence showed that there are strong correlations between cumulative subsidence and floor area (or rail mileage).
- (3) Factors resulting in land subsidence during urbanisation include additional loads during and after construction, underground structure construction involving foundation engineering and construction of tunnels and reduction in the groundwater level due to tunnel leakage and decreased groundwater recharge from the surroundings (e.g., suburban pumping and cut-off effects of underground structures).
 - (4) Further research needs to be carried out to investigate how these factors contribute to land subsidence in Shanghai.

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