Nat Hazards (2018) 91:1341–1363
https://doi.org/10.1007/s11069-018-3189-z

ORIGINAL PAPER

Zoning of confined aquifers inrush and quicksand in Shanghai region

Guangyun Gao[1,2] · Shaofeng Yao[1,2] · Yujun Cui[3] · Qingsheng Chen[4] · Xianlin Zhang[5] · Kewen Wang[6]

Received: 15 November 2017 / Accepted: 19 January 2018 / Published online: 1 February 2018
© Springer Science+Business Media B.V., part of Springer Nature 2018

Abstract Groundwater inrush and quicksand from the underlying aquifers are two typical geological hazards during underground constructions in Shanghai region, China. The objective of this work is to give a zoning study on confined aquifers and quicksand geology in Shanghai region and provide helpful decision-making information for the government, urban planners and designers. The hydrogeological characteristics of the confined aquifers in Shanghai are collected, and two different criteria are then proposed for mapping

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11069-018-3189-z) contains supplementary material, which is available to authorized users.

✉ Guangyun Gao
gaogy@tongji.edu.cn; gaoguangyun@263.net

Shaofeng Yao
ifengfire@tongji.edu.cn

Yujun Cui
yu-jun.cui@enpc.fr

Qingsheng Chen
ceecq@nus.edu.sg

Xianlin Zhang
935662722@qq.com

Kewen Wang
wangkewen@shckgs.com

1 Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

2 Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 200092, China

3 Laboratoire Navier/CERMES, Ecole des Ponts ParisTech, 77455 Marne La Vallée Cedex 2, France

4 Department of Civil and Environmental, National University of Singapore, Singapore 117576, Singapore

5 Shanghai Municipal Bureau of Planning and Land Resources, Shanghai 200003, China

6 Shanghai Changkai Geotechnical Engineering Co., Ltd, Shanghai 200070, China

the aquifers. The characteristics and distribution of the soil stratum, in which quicksand would occur, are then presented, and an index system for quicksand hazard and vulnerability assessment is proposed. Furthermore, the quicksand risk in different zones of Shanghai is evaluated using a semiquantitative approach, and the management zoning is developed by considering the urban planning of Shanghai. The zoning maps of confined aquifers and quicksand risk are obtained, and the high-risk zone can be directly identified from the zoning maps. This is greatly helpful for the future urban planning and underground constructions in Shanghai region. The proposed method for quicksand hazard and vulnerability assessment is also applicable for other cities undergoing geological hazards caused by confined water inrush and quicksand.

Keywords Confined aquifers · Water inrush · Quicksand · Zoning · Risk assessment · Mapping

1 Introduction

Shanghai region covers a total area of 6340 km^2 and is located on the deltaic deposit of Yangtze River with an average altitude of 4.0 m above the sea level. With the dramatically quick development and utilization of underground space, many underground infrastructures have been built, such as cross-river tunnels, deep basement of high-rise buildings and metro lines (Chen et al. 2011; Gao et al. 2012; Wu et al. 2016). This trend of underground constructions is easing the space insufficiency caused by the limited ground space; nevertheless, it constitutes a big challenge from a practical point of view because of the detrimental hydrogeological and geological conditions (Huang et al. 2015; Wu et al. 2015b, 2017; Xu et al. 2009).

Indeed, the widely distributed Quaternary deposit contains abundant underground water; most of which are confined water that may lead to problems such as water inrush, leakage, foundation corrosion and floatation of underground structures. Moreover, sand strata with different thicknesses are also extensively distributed in these shallow stratum (Shen and Xu 2011; Shen et al. 2013). As a result, quicksand often occurs resulting from the interaction between the confined water and sand strata, leading to serious problems such as foundation pit instability, bottom hydraulic heave and even collapse of underground structures (Shi 2010). For example, a serious accident causing huge economic loss of approximately 227 million dollars (USD) occurred on July 1, 2003, during the construction of Shanghai Metro Line 4, due to the confined water inrush and accompanied quicksand at the connected aisle of the tunnel (Shen et al. 2014; Wu et al. 2015a; Elbaz et al. 2016). Thereby, the two geological hazards—groundwater inrush and quicksand—have become the main concern in exploitation of underground space in Shanghai, and it is of paramount importance to understand the characteristics and distribution of the confined aquifers and soil stratum to manage such hazards.

Many studies have been conducted to evaluate hazards induced by confined aquifer, such as water inrush and land subsidence (Shen and Xu 2011; Wu et al. 2015a, b, c, 2014; Xu et al. 2012a, b). For Shanghai city, a series of investigations were conducted dealing with the problem caused by underground water. For example, Luo et al. (2015; Shen et al. 2014; Xu et al. 2009) elaborated on the hydrogeological characteristics of Shanghai geology and pointed out that Quaternary deposit in Shanghai region is composed of a layered multi-aquifer-aquitard system (MAAS). Xu et al. (2009), Huang et al. (2015) and Elbaz et al.

(2016) studied the potential hazards during the underground construction and mentioned that MAAS with soft soil layers, sand strata and high water content aquifers would be more easily disturbed by underground engineering construction, thus causing water inrush and quicksand disasters. Chai et al. (2004), Shen et al. (2013) and Xu et al. (2008, 2012a, b, 2015) investigated the land subsidence hazard caused by underground water pumping and pointed out that local hazards were more significant than overall hazards so that zoning is required (Shen et al. 2014; Wu et al. 2015a).

To study the geological hazards such as landslide and flood, zoning maps are often adopted (Akbar and Ha 2011; Fell et al. 2008; Ganapathy and Rajawat 2015; Liu et al. 2017; Stevens and Hanschka 2014; Thierry et al. 2008). The zoning studies to groundwater are crucial to prevent the occurrence of accidents caused by water inrush (Béjar-Pizarro et al. 2017; Wu et al. 2014). Owing to the significant regional characteristics of aquifers distribution in Shanghai region, zoning of aquifers was also conducted over the past years. For instance, Shi (2010) analyzed the characteristics and groundwater levels of the feeble confined aquifer and Aquifer I and proposed a zoning map of water inrush. Sun et al. (2010) developed a zoning map for Aquifers I and II with consideration of the roof depths of confined aquifers. Nevertheless, the two aforementioned studies were limited to the feeble confined aquifers, Aquifers I and II. Moreover, the zoning of aquifers was mainly carried out for the central district of Shanghai, with separate consideration of the influences of groundwater level and aquifers roof depths.

Quicksand, as a local geological hazard, is often disastrous. To reduce the damage caused by geological hazards, risk assessment was widely used as an effective method (Buttrick et al. 2001; Hsu et al. 2013; Kijko et al. 2002, 2003; Michael-Leiba and Baynes 2002; Peng and Wang 2015; Qi et al. 2017; Zhou and Chen 2008). According to the Asian Disaster Reduction Center for disaster risk management (ADRC 2005), the risk level of geological hazard is evaluated by two factors, i.e., the hazard and the vulnerability of disaster bearing bodies. The former component mainly focuses on the natural attributes of hazard risk, while the latter emphasizes the comprehensive social and economic impacts of the hazard and the resilience capability of the community (Bednarik et al. 2012; Cutter et al. 2008a, b; Dewan 2013; Fuchs et al. 2012, 2016; Westen et al 2008; Yoon 2012). This point of view is also verified by many other researchers (Schneiderbauer and Ehrlich 2004; Wolf 2012; Zhou and Chen 2008). In addition, the vulnerability of geological hazard is concerned by more and more scholars (Ahmed and Dewan 2017; Fuchs et al. 2012; Huang et al. 2011; Lummen and Yamada 2014; Usha et al. 2012; Westen et al. 2008; Wisner et al. 2004). And vulnerability assessment has been becoming widely applied in the prevention of geological disasters, including landslide, flood and seismic (Ahmed and Dewan 2017; Alam et al. 2012; Bender 2002; Huang et al. 2011; Sowmya et al. 2015; Nie et al. 2017).

To date, study on quicksand risk is rare. Lots studies concerning quicksand were aimed to reveal its mechanism (e.g., El Shamy and Zeghal 2005; Fujisawa et al. 2013; Sun 2016). To mitigate the local quicksand risk in Shanghai region, Shi (2010) estimated the occurrence probability of quicksand in central urban area, based on the regional characteristics of sand strata. However, this study was limited to the natural attributes of quicksand, while the vulnerability assessment was not considered. As a typical geological hazard, the vulnerability assessment of quicksand is essential in the quicksand risk assessment without exception. Therefore, a reasonable assessment and zoning study of the quicksand risk considering both its hazard and vulnerability are quite necessary for the Shanghai region.

The objective of this study therefore is to develop a zoning map of confined aquifers distributed throughout the entire Shanghai region in terms of its hydrogeological characteristics and evaluating the quicksand hazard, vulnerability and risk. In terms of large test data obtained from laboratory and field investigations, aquifer zoning maps, quicksand risk and its management zoning maps are developed, which give an overall view about the hydrogeological conditions in Shanghai and provide helpful information for the future urban planning and underground constructions, thereby mitigating the disasters caused by confined water inrush and quicksand.

2 Hydrogeological characteristics of confined aquifers in Shanghai region

The confined water in Shanghai region is located in six aquifers which are separated by five clayey aquitards. The typical profile and geological characteristics of soil layers are shown in Table S1 in ESM (Chen et al. 2011; SUCTC 2012). For the underground constructions in this region, the maximum excavation depth has reached 41 m (Xu et al. 2009). At this depth, it involves the feeble confined Aquifer ⑤$_2$, Aquifers I and II corresponding to Layer No. ⑦ and ⑨ (note that labels ⑤$_2$, ⑦ and ⑨ are the same as the standard hierarchical labels in the SUCTC 2012, as specified in Table S1 in ESM). In the following sections, the distribution and characteristics of these aquifers are presented and discussed.

2.1 Characteristics of the feeble confined ⑤$_2$ aquifer

The artesian aquifer above soil layer ⑦ is often dubbed the feeble confined aquifer and mainly buried in layer ⑤$_2$. This aquifer is in silty soil, fine sand, silty sand and silty sand imbedding in the thin silty clay and has a wide variability in the region of paleochannel, the three islands of Chongming District (namely Chongming Island, Changxing Island and Hengsha Island) and the southern part of the center city (SIGS 2008).

The roof depth of this ⑤$_2$ aquifer varies from – 10 to – 40 m. (The standard Wusong elevation (SLRMB 2010) is used as the base level.) The buried depth is up to – 30 to – 40 m and – 40 to – 50 m in some parts in the three islands of Chongming District (SIGS 2008; Wei et al. 2010).

This aquifer has a poor water quality (Shi 2010; SLRMB 2010). The groundwater level (hereinafter referred to as water level) is seasonally influenced by the meteorology, hydrology and irrigation. Monitoring data show that the water level is generally below – 4 m in the south of the central city (particularly on both sides of the Huangpu River around the Expo site area) and is higher than – 2 m outside the central city and at – 1 to – 3 m in other regions as shown in Table S1 in ESM.

2.2 Characteristics of the ⑦ Aquifer I

The aquifer buried in soil layer ⑦ is called Aquifer I (SUCTC 2012). The soil layer is mainly composed of sandy silt, silty sand and silty-fine sand. The soil type gradually varies from fine to coarse sand with increasing depth (Shi 2010). Aquifer I is widely distributed in Shanghai, but it is absent in the north and west of Shanghai, including Chongming District, some local area of Jiading, Baoshan, Jinshan Districts and the region surrounding Dianshan Lake in Qingpu District. The thickness and depth of Aquifer I have a large difference in different regions due to the cutting effect of paleochannel. Generally, it is thin (about 5–11 m) in the west area of paleochannel, but it is thick (about 11–37 m) in the eastern and the normal sedimentary area. The thickness ranges from 5 to 37 m, and the roof elevation lies between – 11 and − 43 m (− 11 to − 19 m in the north and west, − 19 to − 35 m in the central city, and – 35 to − 43 m in the eastern and southern) (SIGS 2008; Wei et al. 2010).

The water level of Aquifer I is stable with time at one site, but it varies spatially (Shi 2010; SLRMB 2010). Monitoring data indicate that the water level varies in the range from 0 to − 4 m and decreases and then increases from the south to north. The water level is high in Baoshan District, Yangpu District and Gaoqiao area in north Pudong New District, being at 0 to − 2 m, but the water level is low in the Putuo, Jingan Districts and the Jinqiao area in Pudong New District, being at – 3 to − 4 m; it is about − 2 m in south districts including Jinshan, Fengxian and Pudong Districts; the south Tangqiao and the Expo area have the lowest water level at around − 4 m, as shown in Table S1 in ESM.

2.3 Characteristics of the ⑨ Aquifer II

The aquifer buried in the ⑨ soil layer is named Aquifer II (SUCTC 2012). This widely distributed aquifer is absent in the outcrop bedrock areas. This soil layer contains gravelly coarse-medium sand, fine-medium sand and silty-fine sand, with the particle size increasing with depth (Shi 2010). The thickness ranges from 10 to 70 m, and the roof elevation lies at – 60 to − 65 m in the north and the central city, while – 65 to − 70 m in the other regions (SIGS 2008; Wei et al. 2010).

The water level of Aquifer II is stable in different regions (SLRMB 2010). Monitoring data show that the water level lies at 1 m to − 1 m in the three islands of Chongming District, at – 3 to − 6 m in Jiading District and Baoshan District and at − 4 m in central city; it is at − 3 to − 8 m in the center and south part, at – 2 to − 15 m in west part and deep to − 20 m in some areas of northwestward Jinshan District, as shown in Table S1 in ESM.

From the analysis on the above three aquifers, it can be seen that: (a) the soil layers mostly consist of silty sandy soil and sandy soil; (b) the aquifers have regional characteristics in burial conditions and distributions and vary significantly in roof depth and thickness; (c) the water level is stable in general but also varies greatly in different areas; (d) most aquifers have high water content and high water head (higher than 8 m). From a practical point of view, it is of great importance to develop a zoning map of the aquifers in terms of hydrogeological characteristics for guiding the future urban planning and underground construction in Shanghai region. In the next section, aquifer zoning is conducted based on the above characteristics of confined aquifers.

3 Zoning of the confined aquifers in Shanghai region

For the construction projects at their preliminary planning stage (Stage I) and design/construction stage (Stage II), the zoning of the confined aquifers is developed based on two different criteria incorporating different requirements of the projects at different stages. Detailed information is presented in the following section:

3.1 Aquifer zoning for projects at stage I

At stage I, it is expected to have the general distribution of the groundwater in the region. Hence, the criteria for zoning the acquirers only account for the number of the aquifers in the zone. As a result, as shown in Table 1, the confined aquifers are firstly divided into 3 zones I, II and III, based on the number of the aquifers in each zone. Zones I and II are then, respectively, divided into 2 and 3 sub-zones according to the types of aquifers. It is found that the feeble confined aquifer is located at the ⑤$_2$ soil layer, while Aquifer I and Aquifer II are located at the ⑦ and ⑨ soil layer, respectively.

Based on the above criteria together with the basic geological data and the distribution maps of the ⑤$_2$, ⑦ and ⑨ soil layers in Shanghai (SIGS 2008; Wei et al. 2010), the zoning map with a measure scale ratio of 1:20 million is developed, as shown in Fig. 1. It can be observed from Fig. 1 that most districts of Shanghai are located in zone II_3 with complex hydraulic conditions; it is mainly because Aquifers I and II are widely distributed in Shanghai region. Several local areas (e.g., part of Sanxing Town, Miao Tang and Chenjia Town) in the three islands of Chongming District are located in zone I_2; it is mainly because there is a deletion of Aquifer I in Chongming District. The rest areas are mostly located in zone II_2. The northern Jiading and Baoshan Districts have many different zones, including zone I_2, II_2 and II_3. Zone I_1 spreads in the area where the bedrock exposed. Although zone III has a scattered distribution, the water inrush risk here is higher since it contains the feeble aquifer ⑤$_2$, Aquifers I and II. Thus, important project constructions are not recommended in zone III. Since the zone II_3 contains Aquifers I and II, special attention should be paid to mitigate the water inrush when constructions are conducted.

3.2 Aquifer zoning at stage II

At stage II, detailed information about the distribution of groundwater is needed. Therefore, the criteria for zoning the acquirers comprehensively take into account the number of the aquifers in the zone as well as the roof depth and the groundwater level of each aquifer. The detailed zoning criteria of the roof depth and the groundwater level are presented in Table 2. According to the detailed content of national economic and social development plan of Shanghai (SMPG 2011), the three islands of Chongming District would be built as an ecological garden, in which the construction activities would be rare, and these areas are not considered in our study. The confined water head (the vertical distance from the top of the confined aquifer to the groundwater level) for the corresponding stratification point is calculated and listed in Table 2. The aquifers are divided into 3 zones, I, II and III. They are divided into I_1, I_2, I_3, II_1, II_2, II_3, III_1 and III_2 with respect to different confined water head, respectively. Moreover, zones III_1 and III_2 are divided into three sub-zones labeled with subscripts a, b and c, respectively.

It can be seen from Table 2 that zones I, II and III have 3, 3 and 6 water heads, respectively, with different combinations. There are 12 (i.e., 3 + 3 + 6) sub-zones for one layer, 45 (i.e., 3 × 3 + 3 × 6 + 3 × 6) sub-zones for two layers and 54 (i.e., 3 × 3 × 6) sub-zones

Table 1 Aquifer zoning for projects at preliminary planning stage considering the number of the aquifers

Zones		Distribution of the three confined aquifers
I	I_1	There is only the first confined Aquifer ⑦
	I_2	There is only the second confined Aquifer ⑨
II	II_1	There exist the feeble Aquifer ⑤$_2$ and first confined Aquifer ⑦ with no second confined Aquifer ⑨
	II_2	There exist the feeble Aquifer ⑤$_2$ and second confined Aquifer ⑨ with no first confined Aquifer ⑦
	II_3	The first and second confined aquifers ⑦ and ⑨ with no feeble Aquifer ⑤$_2$
III		There exist the feeble Aquifer ⑤$_2$, first and second confined aquifers ⑦ and ⑨

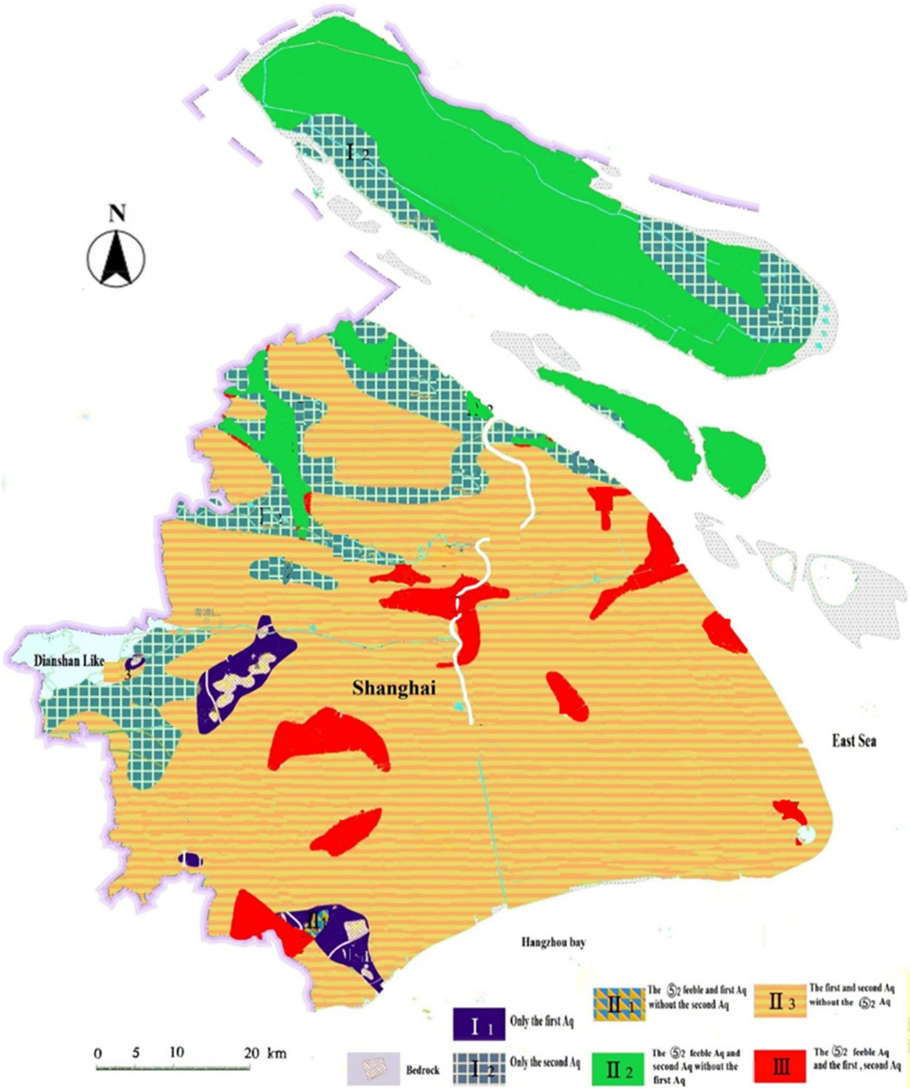

Fig. 1 Zoning map of the confined aquifer in Shanghai for projects at preliminary planning stage considering the number of the aquifers

for three layers. That is, there are 111 sub-zones in total for the aquifer zoning. However, because some of the combinations of aquifers actually do not exist according to the distribution map of aquifers, 48 combinations of zones of confined aquifers are proposed as shown in Table S2 in ESM. Accordingly, in terms of the zoning criteria for Stage II together with the related distribution geological maps of the ⑤$_2$, ⑦ and ⑨ soil layers, the roof elevation maps (SIGS 2008; Wei et al. 2010) and the water level distributing maps of the three aquifers (SLRMB 2010), the zoning map of the aquifers with a measure scale ratio of 1:20 million is developed as shown in Fig. 2.

Table 2 Aquifer zoning for projects at design and construction stages considering the distribution, the roof depth and the groundwater level of the aquifers

Zones			Characteristics in the zone			
			Aquifer	Roof depth (m)	Groundwater level (m)	Water head (m)
I	I_1		The feeble confined Aquifer ⑤$_2$	− 10 to − 20	About − 2 m	8–18
	I_2			− 20 to − 30		18–28
	I_3			− 30 to − 40		28–38
II	II_1		The first confined Aquifer ⑦	− 11 to − 19	0 to − 4	7–19
	II_2			− 19 to − 35		15–35
	II_3			− 35 to − 43		31–43
III	III_1	a	The second confined aquifer ⑨	− 60 to − 65	− 2 to − 6	54–63
		b			− 6 to − 10	50–59
		c			− 10 to − 20	40–55
	III_2	a		− 65 to − 70	− 2 to − 6	59–68
		b			− 6 to − 10	55–64
		c			− 10 to − 20	45–60

From Fig. 2 and Table S2 in ESM, it can be found that most regions of Shanghai belong to the zones with two aquifer layers, such as $II_1 + III_{1\text{-}a}$, $II_2 + III_{1\text{-}a}$, $II_2 + III_{2\text{-}a}$, $II_3 + III_{1\text{-}a}$ and $II_3 + III_{2\text{-}a}$. These zones are composed of zone II and the high-pressure area of zone III. Zone II includes aquifer I and Zone III includes aquifer II, and both of them have a high water head, which can be observed in Table 2. The zone III mainly consists of subzone $III_{\text{-}a}$, except for sub-zone $III_{\text{-}c}$ in the southwest region and $III_{\text{-}b}$ in the southwest narrow banded region. Most administrative district (except for Fengxian and Qingpu Districts) contains zones II_2+$III_{1\text{-}a}$ and II_3+$III_{2\text{-}a}$, with complex hydraulic conditions. Effective countermeasures should be taken to mitigate the water inrush when constructions are conducted in these areas.

The two-stage zoning maps give an overall view of the water inrush in this region, which would be helpful to the government, urban planners and designers. However, it should be noted that, for the engineering and technical analysis of a specific project, detail engineering data of the construction site should be referred to obtain the specific hydrogeological information of confined aquifers.

4 Quicksand characteristics and assessment

Quicksand is known as a sudden suspension flow phenomenon of saturated loose soil under water pressure (resulting from the water head difference or hydraulic gradient), which could lead to significant damage to the underground constructions. The critical sate governing the occurrence of quicksand is closely associated with the following three typical aspects (SUCTC 2012):

(i) *Engineering geological conditions* Quicksand occurs mostly in the silty-fine sand layer with uniformly distributed particle size, and sometimes in silty soil;

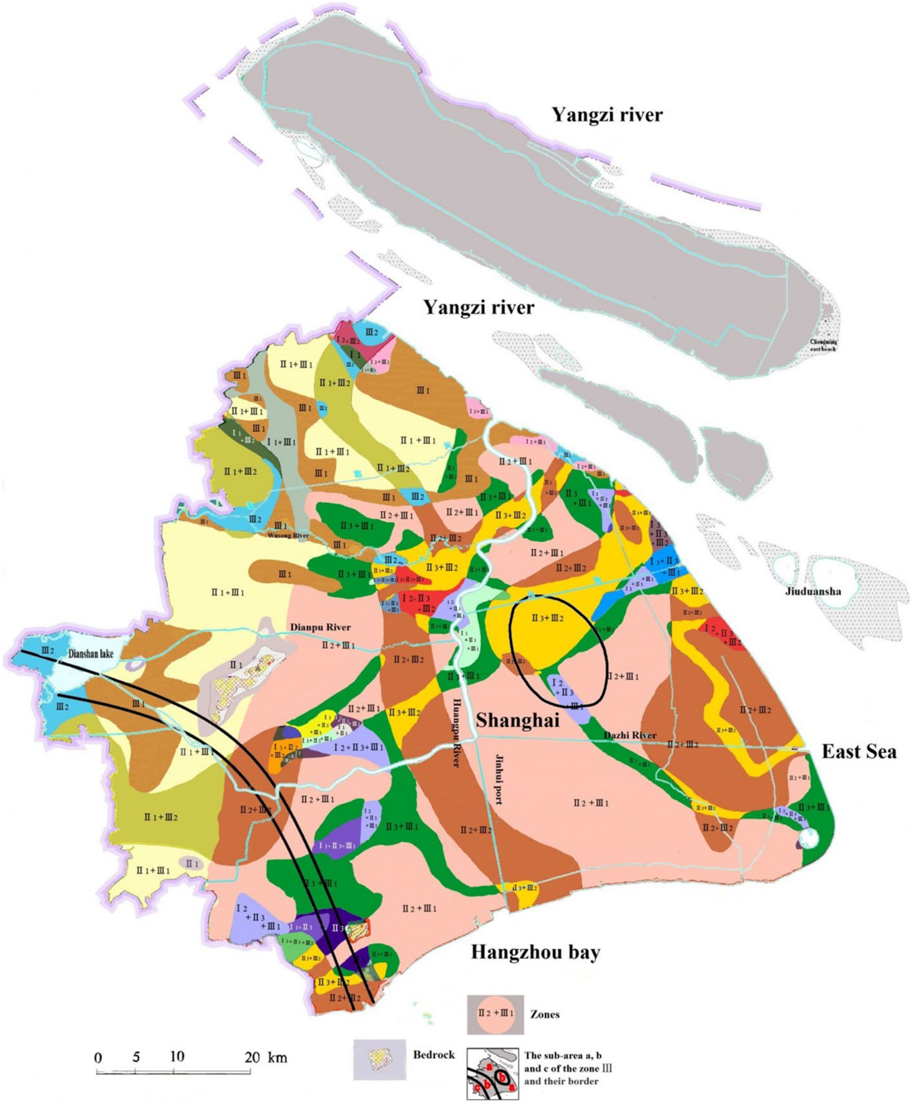

Fig. 2 Zoning map of the confined aquifer in Shanghai for projects at design and construction stage considering the distribution, the roof depth and the groundwater level of the aquifers. (Reproduced with the permission from SIGS 2008; Wei et al. 2010)

(ii) *Groundwater condition* The groundwater level higher than the depth of the sand layer makes the soil layer saturated, which is an essential condition for quicksand;

(iii) *Artificial factor* Operations such as pit or tunnel excavation often result in free face and changes in groundwater level.

4.1 Characteristics and distribution of soil with high vulnerability for quicksand

The collected data for the Shanghai region (SUCTC 2012) show that the soils with high vulnerability for quicksand have the following main characteristics: (a) the silty sand, sandy silt, silt and sand layers with a thickness of more than 0.25 m; (b) the clay-size fraction is less than 10% and the silt-size fraction is more than 75%; (c) the coefficient of uniformity is less than 5; (d) the porosity is higher than 43%; (e) the water content is higher than 30%; (f) the soil is in a saturated state; (g) the soil has a low permeability and a poor drainage condition.

On the other hand, the underground constructions are generally conducted at a shallow depth, 60 m beneath the ground surface. For example, the excavation depth of Yishan Road Station, the transfer station of Shanghai Metro Line 3, 4 and 9, was 29.7 m and the retaining wall was constructed to a depth of 62.9 m (Shen et al. 2014). The soil strata in this zone can be divided into 7 layers, i.e., the ①–⑦ layers (SUCTC 2012). Quicksand mainly occurs at the ②$_0$ layer, the ②$_3$ layer, the ③$_2$ layer, the ⑤$_2$ layer and the ⑦ layer. The distribution and characteristics of these layers are presented in Table S3 in ESM (SIGS 2008; Wei et al. 2010).

4.2 Characteristics of the quicksand risk in Shanghai region

Quicksand risk needs to be evaluated in terms of hazard occurrence and damage level to human beings and society. In the Shanghai region, sand strata with high water head can be easily disturbed by underground engineering construction, which is the main cause of quicksand disasters (Elbaz et al. 2016; Luo et al. 2015; Shen et al. 2014; Xu et al. 2009). The recent historic cases indicate that the quicksand risk has the following characteristics (Tang et al. 2016): firstly, most of the quicksand occurred suddenly and the destructive process completed in a very short time (Shen et al. 2014; Xu et al. 2009). Secondly, the hydrogeological conditions as well as the social and economic conditions of the zone where quicksand occurred differ significantly from each other. Finally, the human activities such as foundation pit excavation, tunnel excavation are often the decisive factor to trigger the occurrence of quicksand, especially when the design and construction are improper (Elbaz et al. 2016). However, the quicksand risk can be effectively reduced to an acceptable level through a reasonable design, construction and scientific monitoring.

4.3 The assessment index system of quicksand risk

Although the occurrence probability of quicksand has been investigated for hazard assessment in the central urban area in Shanghai (Shi 2010), little attention has been paid to the vulnerability with respect to quicksand even though it has been reported that vulnerability analysis and assessment can contribute significantly to geohazard risk reduction (Fuchs et al. 2012; Lummen and Yamada 2014; Usha et al. 2012; Westen et al. 2008). To perform a further assessment of quicksand risk, a novel assessment index system considering both the *hazard* factor and the *vulnerability* factor is proposed, as illustrated in Fig. 3. The *hazard* factor mainly refers to dynamic conditions such as hydrogeological conditions, meteorological conditions, construction activities, which would lead to the occurrence of quicksand. In contrast, the vulnerability factor reflects the potential total maximum losses caused by quicksand for the specified area and during a reference period of time. The impact on the built environment may be measured by the population size and density—with a densely populated area being more vulnerable to quicksand than a sparsely populated one. The vulnerability of property mainly attributes from losses due to damage of the physical infrastructure and buildings. The economic vulnerability can be measured in terms of the gross domestic product (GDP), which is an index that reflects the degrees of social prosperity, economic development and the disaster recovery capacity of an area (Schneiderbauer and Ehrlich 2004). Economic vulnerability to quicksand disaster is greater in areas with higher the GDP. With respect to quicksand, land resources are the main contributor to resource and environmental vulnerability and may be approximately measured by the total residential investment. Obviously, an area with high land value should be rated as having higher resource vulnerability because it would suffer a greater loss when quicksand occurs. In the hazard-affected area, the resistance capability of the habitat environment, the life and property to the disaster as well as the resilience ability of post-disaster reconstruction reduce with the increase of population density and property density (Schneiderbauer and Ehrlich 2004).

5 Quicksand risk assessment and its management zoning

The level of quicksand risk is the interplay between hazard and vulnerability (see Fig. 3). Therefore, the whole risk assessment and zoning of the quicksand disaster include three aspects: hazard analysis, vulnerability analysis and risk assessment (see Fig. 4), as discussed in the following sections.

5.1 Quicksand hazard zoning

The aim of the quicksand hazard zoning is to derive the occurrence probability in different locations in the region. The hazard analysis mainly considers the operation and hydrogeological conditions, meteorological conditions and anthropogenic geological activities mentioned above. According to the literature (Deng et al. 2016) and a series of meteorological survey data provided by the Shanghai City Planning and Land Resources Management Bureau (SLRMB 2010), there is a good correlation between meteorological conditions and hydrogeological conditions in Shanghai region. As for the anthropogenic geological activity, it would vary for different projects and should be analyzed for the specific construction conditions of the project. Therefore, the hazard zoning is conducted mainly based on the hydrogeological conditions (distribution of sand strata and the aquifers).

The distribution of the ①$_3$ layer is quite narrow, and the ②$_0$ layer is only distributed at some shore areas along the Huangpu river, while the ③$_2$ layer scatters in some local area as a small interbed. For the groundwater condition, the construction projects would be mainly affected by the feeble confined aquifer, Aquifers I and II (Xu et al. 2009; Sun et al. 2010). The phreatic water is widely distributed and has a relatively stable feature. It is found that the feeble confined aquifer located at the ⑤$_2$ soil layer, Aquifer I located at the ⑦ layer and Aquifer II at the ⑨ soil layer, respectively. That is, there is a one-to-one correspondence between the quicksand stratum and the aquifers. Because the ⑨ layer is widely distributed and has a stable layer position, this layer can be ignored in the further analysis.

Therefore, in this study the hazard zoning of quicksand in the three quicksand strata, i.e., the ②$_3$, ⑤$_2$ and ⑦ layers in Table S4 in ESM is conducted. Three grade zones, namely the low-, medium- and high-hazard zones of quicksand as well as the corresponding hazard

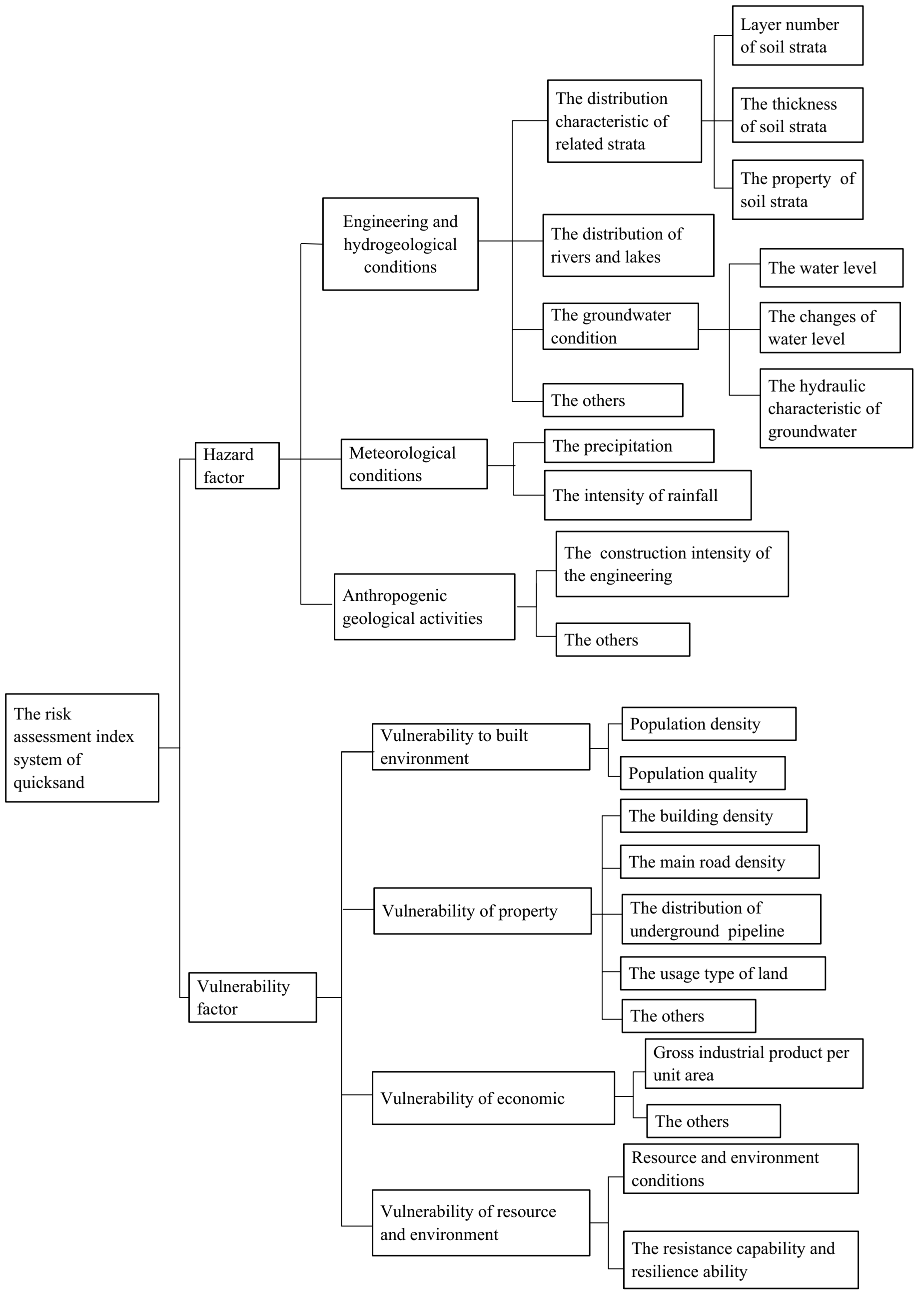

Fig. 3 Diagram of elements and index system for quicksand risk assessment

zoning map, are developed as shown in Fig. 5. The zones with different characteristics are presented in Table 3.

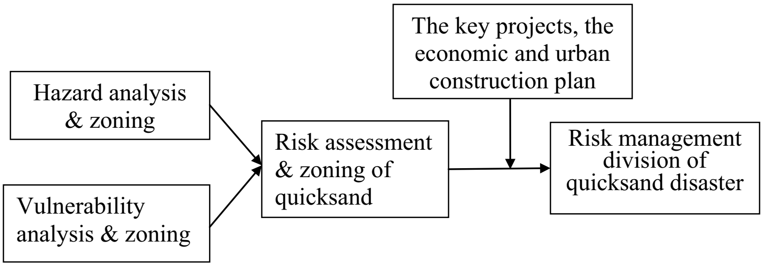

Fig. 4 Procedures of quicksand risk assessment

It can be seen from Fig. 5 that Zones II_1 (medium-hazard zone) and III_2 (high-hazard zone) covered most region of Shanghai with III_3 (high-hazard zone) sparsely scattered, and Zone III_1 (high-hazard zone) and Zone II_2 (medium-hazard zone) covered most area of the three islands of Chongming District. The low hazard zone I is only distributed in some local areas in Songjiang, Jiading and Qingpu Districts. Summarizing, most of Shanghai region has high- and medium-quicksand hazard levels. To avoid the quicksand accidents, particular countermeasures should be taken in these high- and medium-hazard zones.

5.2 Quicksand vulnerability zoning

Vulnerability is a complex, dynamic and multidimensional concept, hazard and scale dependent (Fuchs et al. 2012). As discussed in Sect. 4.3, vulnerability can be mainly considered from four aspects: built environment, property, economic, resource and environment. And vulnerability to community can be evaluated with consideration of the population size and density, the physical infrastructure and buildings, the GDP and residential investment. It may be difficult to access the triggering factors of the risk bearing body for characterizing the regional vulnerability due to the lack of detailed information about the infrastructure and buildings and residential investment. Therefore, a semiquantitative approach was adopted here to estimate the vulnerability of communities. The infrastructure investment, residential investment and GDP of each prefecture in Shanghai region have a strong correlation with its population size and density. That is to say, the size and density of the population in a region can reflect the vulnerability of built environment, economic, property and resources. The area with more developed economy and the higher GDP generally has greater population size and density, thus making greater building and infrastructure densities and higher land values. Therefore, the vulnerability of quicksand was estimated semiquantitatively from the population size and density in the administrative region (including both the central city and suburb) of Shanghai region, which were provided by the Shanghai Municipal Statistics Bureau (SMSB 2010). Table S5 in ESM shows the population size and density of each prefecture of Shanghai at 2010. It is observed that the population size and density have obvious relevance with the administrative unit (city center and suburbs) and have a significant difference in different regions. The population density in the urban center is in the range of 18,031–36,307/km^2 (an average of 24,137/km^2); the suburban population density is in the range of 3169–7029/km^2 (an average of 4684/km^2); population density of outer suburban district is in the range of 594–2613/km^2 (an average of 1388/km^2). And the areas surrounding the administrative center also have a bigger population density. According to the above reasons, we classify the quicksand vulnerability in Shanghai region into three levels: low, medium and high. The scope of administrative units

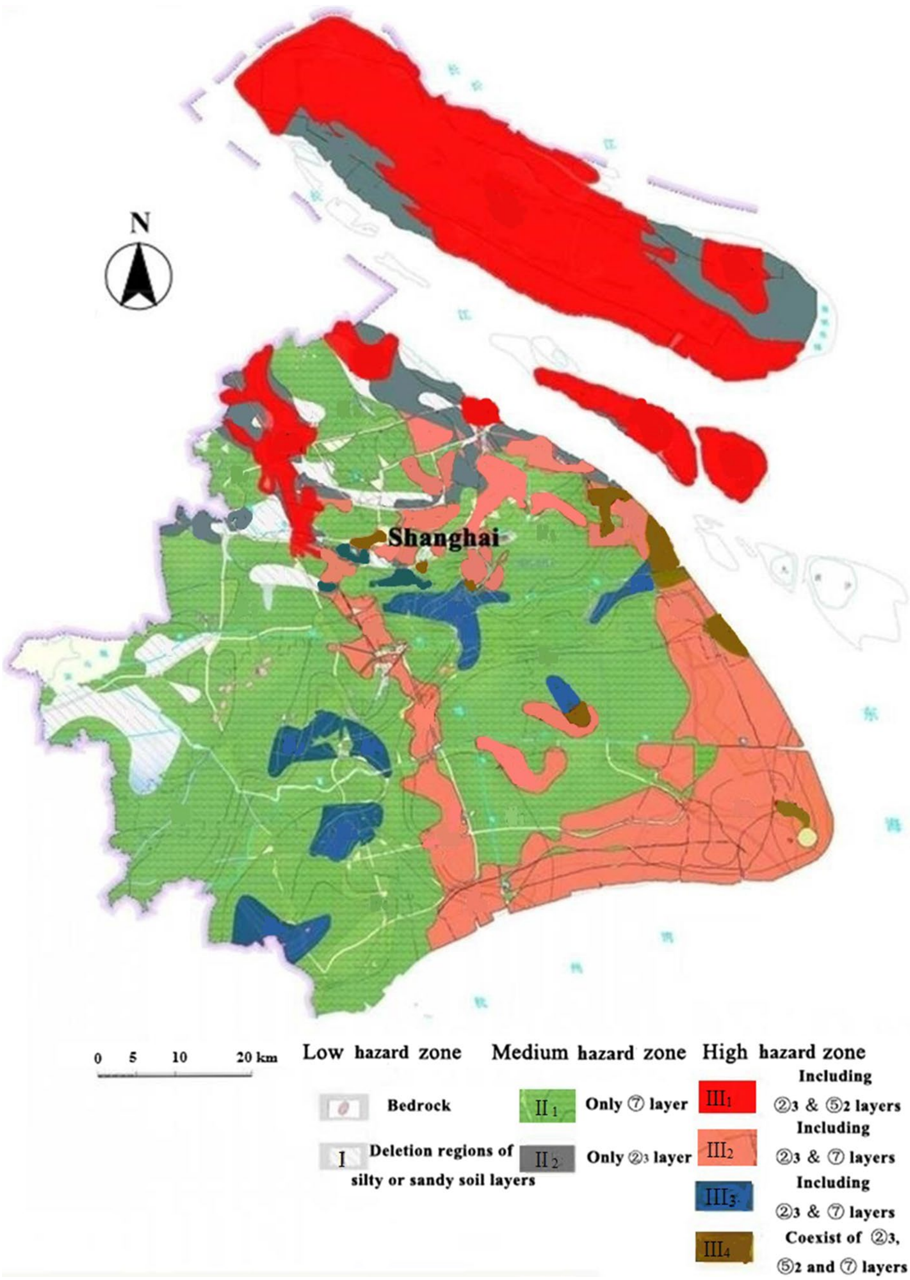

Fig. 5 Hazard zoning map of quicksand in Shanghai. (Based on SIGS 2008; Wei et al. 2010)

of each vulnerability level is indicated in Table S6 in ESM. Quicksand vulnerability zoning map was finally developed and three zones, namely the low zone I, medium zone II and high zone III are shown in Fig. 6. It can be seen that the central city, Lujiazui area along

Table 3 Hazard zoning of quicksand and the characteristic of each zone in Shanghai

Hazard zones			Distribution of the silty, sandy soils in the zones
Low zone	I		Areas of the absence silty, sandy soils; the bedrock exposed areas
Medium zone	II	II_1	Areas only distributed the ⑦ layer
		II_2	Areas only distributed the ②$_3$ layer
High zone	III	III_1	Areas distributed both the ②$_3$ and ⑤$_2$ layers
		III_2	Areas distributed both the ②$_3$ and ⑦ layers
		III_3	Areas distributed both the ⑤$_2$ and ⑦ layers
		III_4	Areas simultaneously distributed the ②$_3$, ⑤$_2$ and ⑦ layers

the Huangpu River in Pudong New District and the surrounding area of each administrative center lie in the high vulnerability zone of quicksand; the original Pudong, Minhang and Baoshan Districts which are adjacent to the central city generally lie in the medium-vulnerability zone, except for some scattered high vulnerability zones; the rest areas which are considerable large mostly lie in low vulnerability zone with some scattered high vulnerability zones. As can be observed, the distribution of quicksand vulnerability has different characteristics with the quicksand hazard. Areas with high hazard level may on the contrary have low vulnerability level, just as the three islands of Chongming District and east region of Shanghai. This would affect the quicksand risk discussed in the next section.

5.3 Assessment and zoning of quicksand risk

The quicksand risk level is determined by multiplying the hazard and vulnerability of the quicksand (ADRC 2005):

$$\text{Risk} = \text{hazard} \times \text{vulnerability} \tag{1}$$

To provide a practical reference for the prevention of the quicksand risk in Shanghai region, the assessment and zoning of the quicksand risk are conducted on the basis of the quicksand hazard and vulnerability evaluation. For simplicity, the low, medium to high quicksand hazard and vulnerability levels are quantified by values of 1, 2 and 3, respectively. Then, different risk values of 1, 2, 3, 4, 6 and 9 as shown in Table 4 can be obtained using Eq. (1). With regard to risk levels 1, 2 and 3, it can be inferred that either the hazard or the vulnerability value is equal to 1, which means a low hazard or vulnerability level. In this case, the quicksand risk is consequently low. With regard to the risk values 6 and 9, it can be inferred that both factors are higher than 2, one being equal to 3. That is to say, the hazard or the vulnerability level lies in the medium or high level zone and one of them is certainly at a high level. In this case, the quicksand risk will be consequently high. For the risk value 4, both the hazard and the vulnerability are at a medium level and the quicksand risk consequently lies in the medium zone. The risk zones of the quicksand elaborated above are presented in Table 5.

The quicksand risk zoning map is established and shown in Fig. 7. It can be found that the high-risk zones are not completely consistent with high hazard and vulnerability zones of quicksand. In the central city, the riverside area along the Huangpu River in Pudong New District and the surrounding area of each administrative center lie in the high quicksand risk zone. Most area of the Pudong, Minhang and Baoshan Districts lie in the

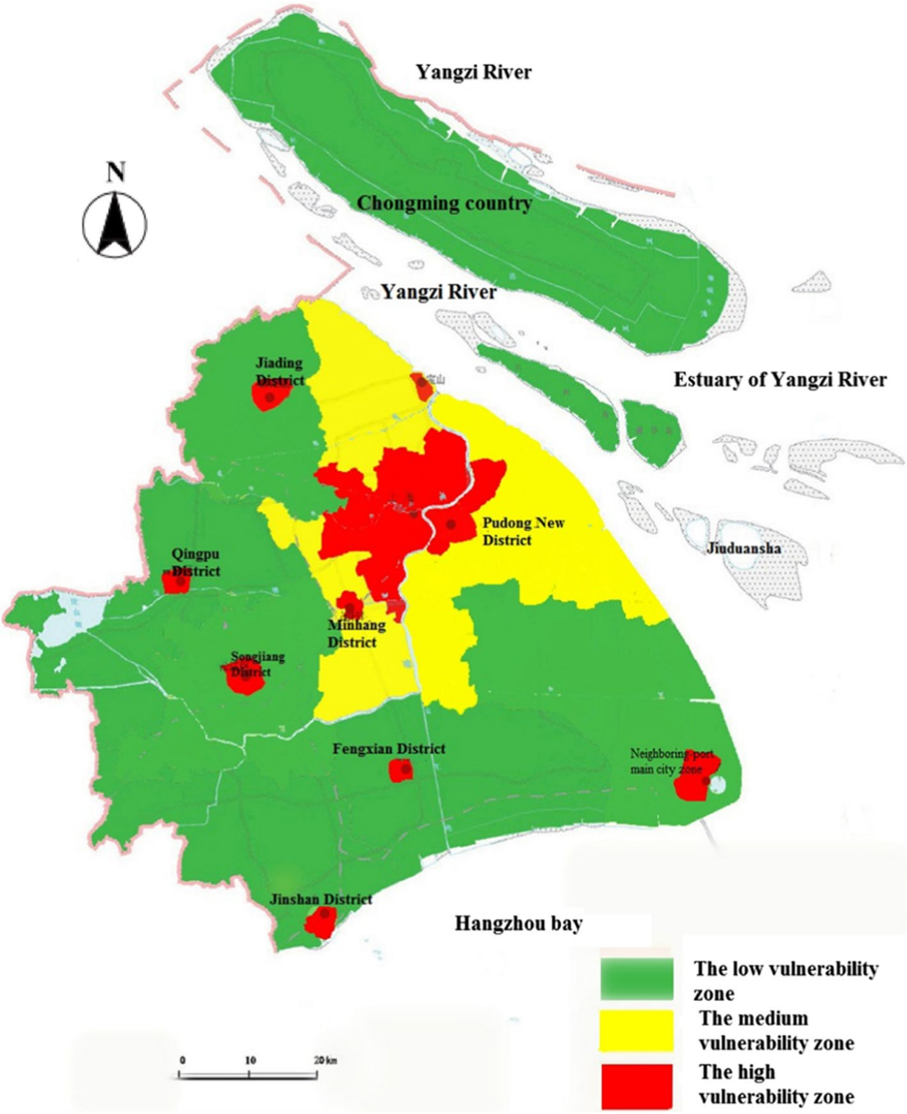

Fig. 6 Vulnerability zoning map of quicksand in Shanghai

Table 4 Hazard, vulnerability and risk levels of quicksand

Vulnerability		Y_1	Y_2	Y_3
Hazard		1	2	3
W_1	1	1	2	3
W_2	2	2	4	6
W_3	3	3	6	9

Table 5 Risk zoning of quicksand

Risk zones	Value of risk degree	Overlap zone condition of the hazard and vulnerability
Low-risk zone I	1, 2, 3	Overlap zones of W_i and Y_1, and W_1 and Y_j ($i, j = 1, 2, 3$)
Medium-risk zone II	4	Overlap zone of W_2 and Y_2
High-risk zone III	6, 9	Overlap zone of W_i and Y_j ($i, j = 2, 3$ and one value has to be 3)

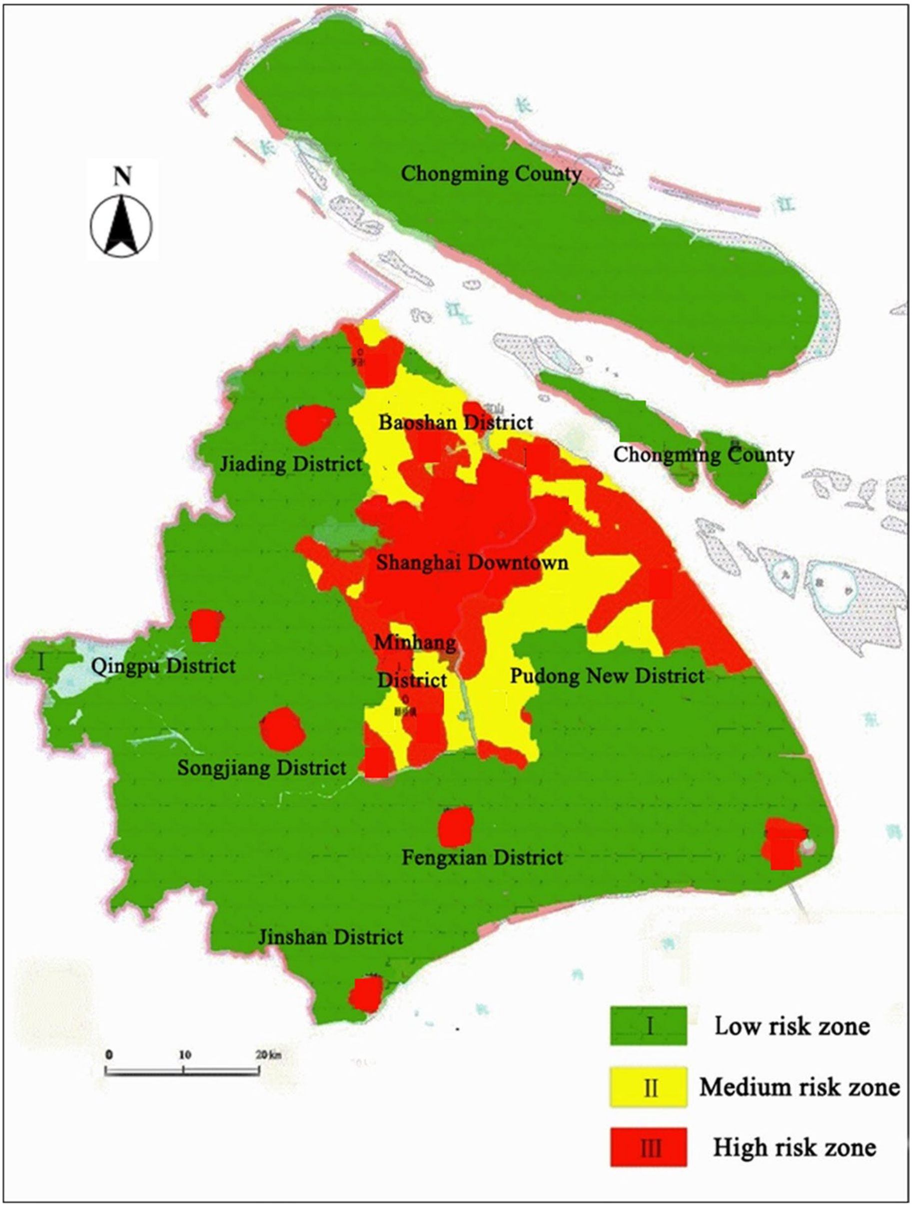

Fig. 7 Risk zoning map of quicksand in Shanghai

medium-risk zone except for some scattered high-risk zones. The rest of the administrative division generally lies in a low-risk zone except for some high zones around the central district. Three islands of Chongming District and east region of Shanghai at high quicksand hazard level have a low-risk level due to their low vulnerability level. Effective measures must be taken to prevent the quicksand disasters before any underground constructions in such medium- and high-risk zones.

5.4 Management zoning of quicksand risk

According to the detailed content of national economic and social development plan of Shanghai (SMPG 2011), Baoshan and Minhang Districts will make further efforts to promote their urbanization level for becoming the expanding area of central city in the near future. A number of industrial projects such as trade zones, bonded areas and industrial parks will be constructed in Pudong District. A series of construction projects will be carried forward along the coastal areas, including Jiading New Town, Songjiang New Town, Qingpu New Town, Pudong Nanhui New Town, Fengxian Nanqiao New Town, Jinshan New Town, Chongming Chengqiao New Town and Chongming District. Based on the development plan (SMPG 2011) and the quicksand risk zoning proposed above, the management of quicksand risk in Shanghai region can be divided into three parts, namely the most-key zone, the sub-key zone and the general-key zone, as illustrated in Table 6 and Fig. 8. It can be found that most parts of Shanghai lies in the most-key and sub-key areas for risk control and management, in which special attention should be paid to mitigate the quicksand risk.

6 Conclusions

The zoning of confined aquifers and quicksand risk in Shanghai region is investigated, and the results allow following conclusions to be drawn:

(1) The zoning of the confined aquifers is developed based two different criteria in terms of different requirements of underground constructions at different stages (I: preliminary planning stage; II: design and construction stage). As a result, the situation and characteristics of the confined aquifers can be directly obtained from the corresponding zoning maps.

Table 6 Risk management zoning of quicksand in Shanghai

Management zones		Range of the management zones
General-key zone	I	Region in the three islands of Chongming District except for the Chengqiao New Town; the area of absence silty, sandy soils layer; the bedrock exposed areas
Sub-key zone	II	Rest regions except for the general-key zone and the most-key zone
Most-key zone	III	The central city; the Minhang and Baoshan Districts and original Pudong New District; New Towns of Jiading, Songjiang, Qingpu, Pudong Nanhui, Fengxian Nanqiao, Jinshan and Chongming Chengqiao; Lingang industry area

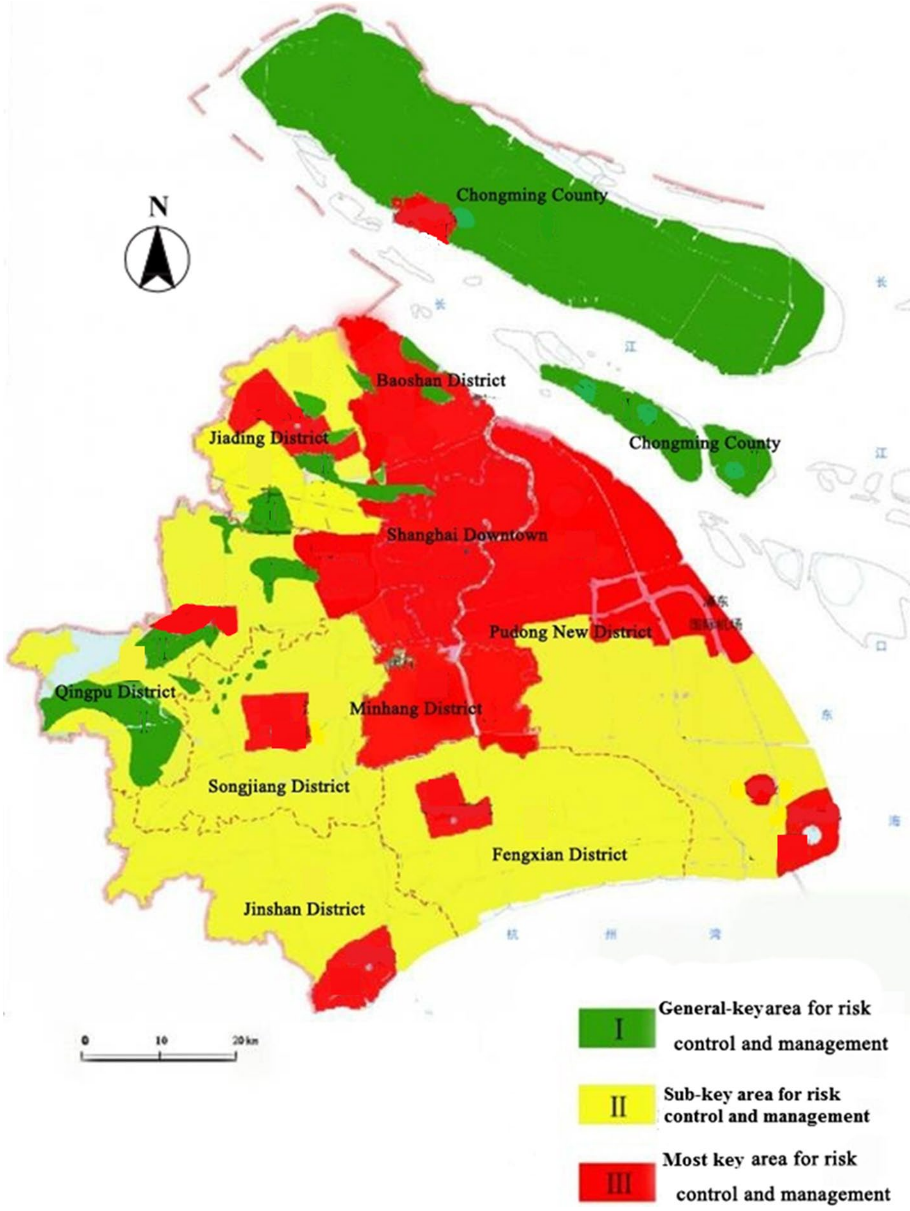

Fig. 8 Risk management zoning of quicksand in Shanghai

(2) According to the zoning for stage I, most of the districts of Shanghai are located in zone II_3 where both Aquifers I and II exist, and the rest areas are mostly located in zone II_2 where both the feeble aquifer and Aquifer II exist. According to the zoning for stage II, most regions of Shanghai belong to the zones that have high water heads, and effective measures should be taken to mitigate the water inrush when constructions are conducted in these areas.

(3) The quicksand risk zoning by incorporating both the quicksand hazard and vulnerability assessments is conducted in Shanghai region. The vulnerability should be considered due to its significant influence on the quicksand risk assessment. Most areas of Shanghai region have a high and medium-quicksand hazard levels. The central city, the riverside area along the Huangpu River in Pudong New District and the surrounding area of each administrative center lie in the high quicksand risk zone. Most area of the Pudong, Minhang and Baoshan Districts lie in the medium-risk zone. According to the management zoning, most areas lie in the most-key and sub-key zones.

This study has clarified the zoning distribution characteristics of hydraulic and geological conditions in Shanghai region. The obtained zoning maps gave an overall view of the water inrush and quicksand risk and provide valuable decision-making information for the government, urban planners and designers. The proposed method can be also extended to other cities by considering the specific hydraulic and geological situations of each city.

Acknowledgements This study was financially supported by the National Natural Science Foundation of China (No. 41772288), which is gratefully acknowledged.

References

Ahmed B, Dewan A (2017) Application of bivariate and multivariate statistical techniques in landslide susceptibility modeling in Chittagong City corporation, Bangladesh. Remote Sens 9(4):304. https://doi.org/10.3390/rs9040304

Akbar TA, Ha SR (2011) Landslide hazard zoning along Himalayan Kaghan Valley of Pakistan—by integration of GPS, GIS, and remote sensing technology. Landslides 8(4):527–540. https://doi.org/10.1007/s10346-011-0260-1

Alam N, Alam MS, Tesfamariam S (2012) Buildings' seismic vulnerability assessment methods: a comparative study. Nat Hazards 62(2):405–424. https://doi.org/10.1007/s11069-011-0082-4

Asian Disaster Reduction Center (ADRC) (2005) Total disaster risk management: Good practices. Available at http://www.adrc.asia/publications/

Bednarik M, Yilmaz I, Marschalko M (2012) Landslide hazard and risk assessment: a case study from the Hlohovec–Sered' landslide area in south-west Slovakia. Nat Hazards 64(1):547–575. https://doi.org/10.1007/s11069-012-0257-7

Béjar-Pizarro M, Ezquerro P, Herrera G (2017) Mapping groundwater level and aquifer storage variations from InSAR measurements in the Madrid aquifer, Central Spain. J Hydrol 547:678–689. https://doi.org/10.1016/j.jhydrol.2017.02.011

Bender S (2002) Development and use of natural hazard vulnerability-assessment techniques in the Americas. Nat Hazards Rev 3(4):136–138

Buttrick DB, Schalkwyk AV, Kleywegt RJ, Watermeyer RB (2001) Proposed method for dolomite land hazard and risk assessment in South Africa. J South Afr Inst Civil Eng 43(2):27–36. https://doi.org/10.1007/s002540050333

Chai JC, Shen SL, Zhu HH, Zhang XL (2004) Land subsidence due to groundwater drawdown in Shanghai. Geotechnique 54(2):143–147. https://doi.org/10.1680/geot.2004.54.2.143

Chen QS, Gao GY, Yang J (2011) Dynamic response of deep soft soil deposits under multidirectional earthquake loading. Eng Geol 121(1):55–65. https://doi.org/10.1016/j.enggeo.2011.04.013

Cutter SL, Finch C (2008) Temporal and spatial changes in social vulnerability to natural hazards. Proc Natl Acad Sci USA 105(7):2301–2306. https://doi.org/10.1073/pnas.0710375105

Cutter SL, Barnes L, Berry M et al (2008) A place-based model for understanding community resilience to natural disasters. Glob Environ Change 18(4):598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Deng JL, Shen SL, Xu YS (2016) Investigation into pluvial flooding hazards caused by heavy rain and protection measures in Shanghai, China. Nat Hazards 83(2):1–20. https://doi.org/10.1007/s11069-016-2369-y

Dewan A (2013) Floods in a megacity: geospatial techniques in assessing hazards, risk and vulnerability. Springer, Dordrecht

El Shamy U, Zeghal M (2005) Coupled continuum-discrete model for saturated granular soils. J Eng Mech 131(4):413–426. https://doi.org/10.1061/(ASCE)0733-9399

Elbaz K, Shen JS, Arulrajah A, Horpibulsuk S (2016) Geohazards induced by anthropic activities of geoconstruction: a review of recent failure cases. Arab J Geosci 9(18):708–719. https://doi.org/10.1007/s12517-016-2740-z

Fell R, Corominas J, Bonnard C (2008) Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Eng Geol 102(3–4):85–98. https://doi.org/10.1016/j.enggeo.2008.03.022

Fuchs S, Glade T (2016) Foreword: vulnerability assessment in natural hazard risk—a dynamic perspective. Nat Hazards 82(1):1–5. https://doi.org/10.1007/s11069-016-2289-x

Fuchs S, Birkmann J, Glade T (2012) Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. Nat Hazards 64(3):1969–1975. https://doi.org/10.1007/s11069-012-0352-9

Fujisawa K, Murakami A, Nishimura S, Shuku T (2013) Relation between seepage force and velocity of sand particles during sand boiling. Geotech Eng 44(2):9–17

Ganapathy GP, Rajawat AS (2015) Use of hazard and vulnerability maps for landslide planning scenarios: a case study of the Nilgiris, India. Nat Hazards 77(1):1–12. https://doi.org/10.1007/s11069-015-1587-z

Gao GY, Chen QS, He JF, Liu F (2012) Investigation of ground vibration due to trains moving on saturated multi-layered ground by 2.5D finite element method. Soil Dyn Earthq Eng 40:87–98. https://doi.org/10.1016/j.soildyn.2011.12.003

Hsu WK, Chiang WL, Chen CW (2013) Earthquake risk assessment and optimal risk management strategies for Hi-Tech Fabs in Taiwan. Nat Hazards 65(3):2063–2076. https://doi.org/10.1007/s11069-012-0462-4

Huang J, Liu Y, Ma L (2011) Assessment of regional vulnerability to natural hazards in China using a DEA model. Int J Disaster Risk Sci 2(2):41–48. https://doi.org/10.1007/s13753-011-0010-y

Huang Y, Bao Y, Wang Y (2015) Analysis of geoenvironmental hazards in urban underground space development in Shanghai. Nat Hazards 75(3):2067–2079. https://doi.org/10.1007/s11069-014-1414-y

Kijko A, Retief SJP, Graham G (2002) Seismic hazard and risk assessment for Tulbagh, South Africa: part I—assessment of seismic hazard. Nat Hazards 26(2):175–201. https://doi.org/10.1023/A:1015671813315

Kijko A, Retief SJP, Graham G (2003) Seismic hazard and risk assessment for Tulbagh, South Africa: part II—assessment of seismic hazard. Nat Hazards 30(1):25–41. https://doi.org/10.1023/A:1025036409750

Liu J, Wang X, Zhang B, Li J, Zhang J, Liu X (2017) Storm flood risk zoning in the typical regions of Asia using GIS technology. Nat Hazards 87(3):1691–1707. https://doi.org/10.1007/s11069-017-2843-1

Lummen NS, Yamada F (2014) Implementation of an integrated vulnerability and risk assessment model. Nat Hazards 73(2):1085–1117. https://doi.org/10.1007/s11069-014-1123-6

Luo CY, Shen SL, Han J, Ye GL, Horpibulsuk S (2015) Hydrogeochemical environment of aquifers groundwater in Shanghai and potential hazards to underground infrastructures. Nat Hazards 78(1):753–774. https://doi.org/10.1007/s11069-015-1727-5

Michael-Leiba M, Baynes F (2002) Quantitative landslide risk assessment of Cairns. Aust Geomech J 37(3):1–13

Nie CX, Chen QS, Gao GY, Yang J (2017) Determination of seismic compression of sand subjected to two horizontal components of earthquake ground motions. Soil Dyn Earthq Eng 92:330–333. https://doi.org/10.1016/j.soildyn.2016.10.007

Peng SH, Wang K (2015) Risk evaluation of geological hazards of mountainous tourist area: a case study of Mengshan, China. Nat Hazards 78(1):1–13

Qi HL, Tian WP, Zhao F (2017) Risk assessment of snow disaster for trunk highway transportation in Shaanxi, China. Nat Hazards 85(1):523–536. https://doi.org/10.1007/s11069-016-2584-6

Schneiderbauer S, Ehrlich D (2004) Risk hazard and people's vulnerability to natural hazards: a review of definitions concepts and data. European Commission -Joint Research Centre (ERCJRC), Brussels

Shanghai City Planning and Land Resources Management Bureau (SLRMB) (2010) Shanghai Geological Environmental Bulletin (2005–2009) (R). Shanghai, China **(in Chinese)**. Available at http://www.shgtj.gov.cn/dzkc/

Shanghai Institute of Geological Survey (SIGS) (2008) Achievement and application of 3D urban geological survey in Shanghai (R). Shanghai, China **(in Chinese)**. Available at http://www.sigs.com.cn/sigsonlines/

Shanghai Municipal People's Government (SMPG) (2011) Outline of the twelfth five-year plan for economic and social development of Shanghai (2011–2015). Shanghai, China **(in Chinese)**. Available at http://www.shanghai.gov.cn/shanghai/node2314/node25307/node25455/node25457/u21ai489656.html
Shanghai Municipal Statistic Bureau (SMSB) (2010) Shanghai statistical yearbook 2010. Shanghai, China. Available at http://www.stats-sh.gov.cn/data/toTjnj.xhtml?y=2010e
Shanghai Urban-Rural Construction and Transportation Commission (SUCTC) (2012) Code for investigation of geotechnical engineering (DGJ08-37-2012). Shanghai, China **(in Chinese)**
Shen SL, Xu YS (2011) Numerical evaluation of land subsidence induced by groundwater pumping. Can Geotech J 48(9):1378–1392. https://doi.org/10.1139/t11-049
Shen SL, Ma L, Xu YS, Yin ZY (2013) Interpretation of increased deformation rate in aquifer IV due to groundwater pumping in Shanghai. Can Geotech J 50(11):1129–1142. https://doi.org/10.1139/cgj-2013-0042
Shen SL, Wu HN, Cui YJ (2014) Long-term settlement behaviour of metro tunnels in the soft deposits of Shanghai. Tunn Undergr Space Technol 40(12):309–323. https://doi.org/10.1016/j.tust.2013.10.013
Shi YJ (2010) Engineering geological conditions and major geological problems during construction of metro tunnels in Shanghai area. J Eng Geol 18(5):774–780 **(in Chinese)**
Sowmya K, John CM, Shrivasthava NK (2015) Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. Nat Hazards 75(2):1271–1286. https://doi.org/10.1007/s11069-014-1372-4
Stevens MR, Hanschka S (2014) Municipal flood hazard mapping: the case of British Columbia, Canada. Nat Hazards 73(2):907–932. https://doi.org/10.1007/s11069-014-1117-4
Sun YY (2016) Experimental and theoretical investigation on the stability of deep excavations against confined aquifers in Shanghai, China. Ksce J Civil Eng 20(7):2746–2754. https://doi.org/10.1007/s12205-016-0488-3
Sun L, Jun J, Miao JF, Xu LP, Chen LR (2010) Zoning for structural type of confined water bearing layer in Shanghai downtown. Shanghai Geol 1:11–15 **(in Chinese)**
Tang Y, Zhou J, Yang P, Yan JJ, Zhou NQ (2016) Groundwater engineering. Tongji University Press, Shanghai. https://doi.org/10.1007/978-3-662-48581-1
Thierry P, Stieltjes L, Kouokam E, Nguéya P, Salley PM (2008) Multi-hazard risk mapping and assessment on an active volcano: the GRINP project at Mount Cameroon. Nat Hazards 45(3):429–456. https://doi.org/10.1007/s11069-007-9177-3
Usha T, Murthy MR, Reddy NT, Mishra P (2012) Tsunami vulnerability assessment in urban areas using numerical model and GIS. Nat Hazards 60(1):135–147. https://doi.org/10.1007/s11069-011-9957-7
Wei ZX, Zhai GY, Yan XX (2010) Atlas of Shanghai urban geology. Geological Publishing House, Beijing
Westen CJV, Castellanos E, Kuriakose SL (2008) Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. Eng Geol 102(3–4):112–131. https://doi.org/10.1016/j.enggeo.2008.03.010
Wisner B, Blaikie P, Cannon T et al (2004) At risk: natural hazards, people's vulnerability and disasters, 2nd edn. Routledge, London
Wolf S (2012) Vulnerability and risk: comparing assessment approaches. Nat Hazards 61(3):1099–1113. https://doi.org/10.1007/s11069-011-9968-4
Wu Q, Fan ZL, Zhang ZW, Zhou WF (2014) Evaluation and zoning of groundwater hazards in Pingshuo No. 1 underground coal mine, Shanxi Province, China. Hydrogeol J 22(7):1693–1705. https://doi.org/10.1007/s10040-014-1138-9
Wu HN, Shen SL, Liao SM, Yin ZY (2015a) Longitudinal structural modelling of shield tunnels considering shearing dislocation between segmental rings. Tunn Undergr Space Technol 50(2015):317–323. https://doi.org/10.1016/j.tust.2015.08.001
Wu Q, Liu YZ, Luo LH, Liu SQ, Sun WJ, Zeng YF (2015b) Quantitative evaluation and prediction of water inrush vulnerability from aquifers overlying coal seams in Donghuantuo Coal Mine, China. Environ Earth Sci 74(2):1429–1437. https://doi.org/10.1007/s12665-015-4132-1
Wu YX, Shen SL, Wu HN, Xu YS, Yin ZY, Sun WJ (2015c) Environmental protection using dewatering technology in a deep confined aquifer beneath a shallow aquifer. Eng Geol 196:59–70. https://doi.org/10.1016/j.enggeo.2015.06.015
Wu YX, Shen SL, Yuan DJ (2016) Characteristics of dewatering induced drawdown curve under blocking effect of retaining wall in aquifer. J Hydrol 539:554–566. https://doi.org/10.1016/j.jhydrol.2016.05.065
Wu HN, Shen SL, Yang J (2017) Identification of tunnel settlement caused by land subsidence in soft deposit of Shanghai. J Perform Constr Facil 31(6):1–10. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001082

Xu YS, Shen SL, Cai ZY, Zhou GY (2008) The state of land subsidence and prediction approaches due to groundwater withdrawal in China. Nat Hazards 45(1):123–135. https://doi.org/10.1007/s11069-007-9168-4

Xu YS, Shen SL, Du YJ (2009) Geological and hydrogeological environment in Shanghai with geohazards to construction and maintenance of infrastructures. Eng Geol 109(3):241–254. https://doi.org/10.1016/j.enggeo.2009.08.009

Xu YS, Ma L, Du YJ, Shen SL (2012a) Analysis of urbanisation-induced land subsidence in Shanghai. Nat Hazards 63(2):1255–1267. https://doi.org/10.1007/s11069-012-0220-7

Xu YS, Ma L, Shen SL, Sun WJ (2012b) Evaluation of land subsidence by considering underground structures that penetrate the aquifers of Shanghai, China. Hydrogeol J 20(8):1623–1634. https://doi.org/10.1007/s10040-012-0892-9

Xu YS, Yuan Y, Shen SL, Yin ZY, Wu HN, Ma L (2015) Investigation into subsidence hazards due to groundwater pumping from Aquifer II in Changzhou, China. Nat Hazards 78(1):281–296. https://doi.org/10.1007/s11069-015-1714-x

Yoon DK (2012) Assessment of social vulnerability to natural disasters: a comparative study. Nat Hazards 63(2):823–843. https://doi.org/10.1007/s11069-012-0189-2

Zhou PG, Chen HQ (2008) Research on geologic hazard risk management in China based on geologic hazard survey and zoning. Int J Risk Assess Manag 8(4):362–372. https://doi.org/10.1504/IJRAM.2008.019013