Urban land subsidence in China

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Abstract: This paper presents a brief review of urban land subsidence in China. It summarises the main features of urban land subsidence, its investigation and remedial works.

Résumé: Cet article présente de un bref examen affaissement urbain de terre et ses travaux de recherche et réparateurs fabriqués en Chine. En outre, un sommaire sur l'état actuel et des caractéristiques principales de l'affaissement urbain de terre en Chine sont donnés

Keywords: Land subsidence, urban, China

INTRODUCTION

Land subsidence can be defined as the differential sinking of the ground surface with respect to the surrounding terrain or sea level. Land subsidence can result from natural causes such as tectonic motion and sea level rise. Alternatively it can be man-induced by causes such as the withdrawal of groundwater, oil and gas, the extraction of coal and ores and underground excavation of tunnels and caverns. Land subsidence is usually observed as a series of disastrous effects. Examples of these phenomena are the breakage of underground utility lines, seawater intrusion, and settlement of buildings and civil infrastructure. Land subsidence is one of the challenging issues that needs to be addressed in many countries including Australia, China, Egypt, France, Germany, India, Iran, Israel, Italy, Japan, Mexico, Poland, Saudi Arabia, Sweden, the Netherlands, UK and USA.

Land subsidence has occurred in many areas, particularly in densely populated cities throughout the world. Most of the major subsidence areas have probably developed since World War II due to accelerated rates of groundwater abstraction. In 1995 it was reported that there were more than 150 major cities in the world where substantial subsidence was a problem (Barends et al. 1995, 1998). Because of its wide distribution and severe environmental and economic consequences, land subsidence is one of the topics that needs research and technology transfer at an international level.

China, like other countries, has suffered land subsidence since at least 1964 when substantial land subsidence was reported in Shanghai. Over the last twenty years, in particular, the rapid urban and industrial developments in China have resulted in the ever-increasing amounts of land subsidence. This has caused extremely expensive damage to the environment and economy in more than 95 cities. This paper presents a brief review of urban land subsidence its investigation and the remedial works undertaken in China.

CURRENT STATUS AND MAIN FEATURES OF URBAN LAND SUBSIDENCE IN CHINA

General status

Figure 1 shows the distribution of the large and medium-sized cities in China where land subsidence is a problem. The land subsidence can be classified into the following three types of geographic regions (Table 1):

- The coastal plain and river delta regions, such as Sanghai, Tanjin, Ningbo, Suzhou, Wuxi, and Changzhou;
- The plain regions in front of major mountains, such as the North China Plain and Songliao Plain;
- Regions in valleys and basins between mountains, such as Xi'an and Taiyuan.

Table 1. Geographical distribution of major cities where substantial land subsidence in China are occurring

Geographical units	Cities where substantial land subsidence are occurring		
	Number	**Percentage of subsiding cities (total cities:39)**	**City name**
The coastal plain and river delta region	14	36%	Shanghai, Tianjin, Suzhou, Wuxi, Changzhou, Ningbo, Jiaxin, Hezhe, Jiing, Dezhou, Fuyang, Zhanjiang, Haikou, Fuzhou
The plain region in front of major mountains	19	49%	Beijing, Cangtzhou, Hengshui, Renqiu, Hejian, Bazhou, Baoding, Dacheng, Nangong, Feixiang, Handan, Xuchang, Kaifeng, Luoyang, Anyang, Ha'erbing, Daqing, Qiqiha'er, Jiamusi
Regions in valleys and basins among mountains	6	15%	Taiyuan, Datong, Yuci, Jiexiu, Xi'an, Kunming

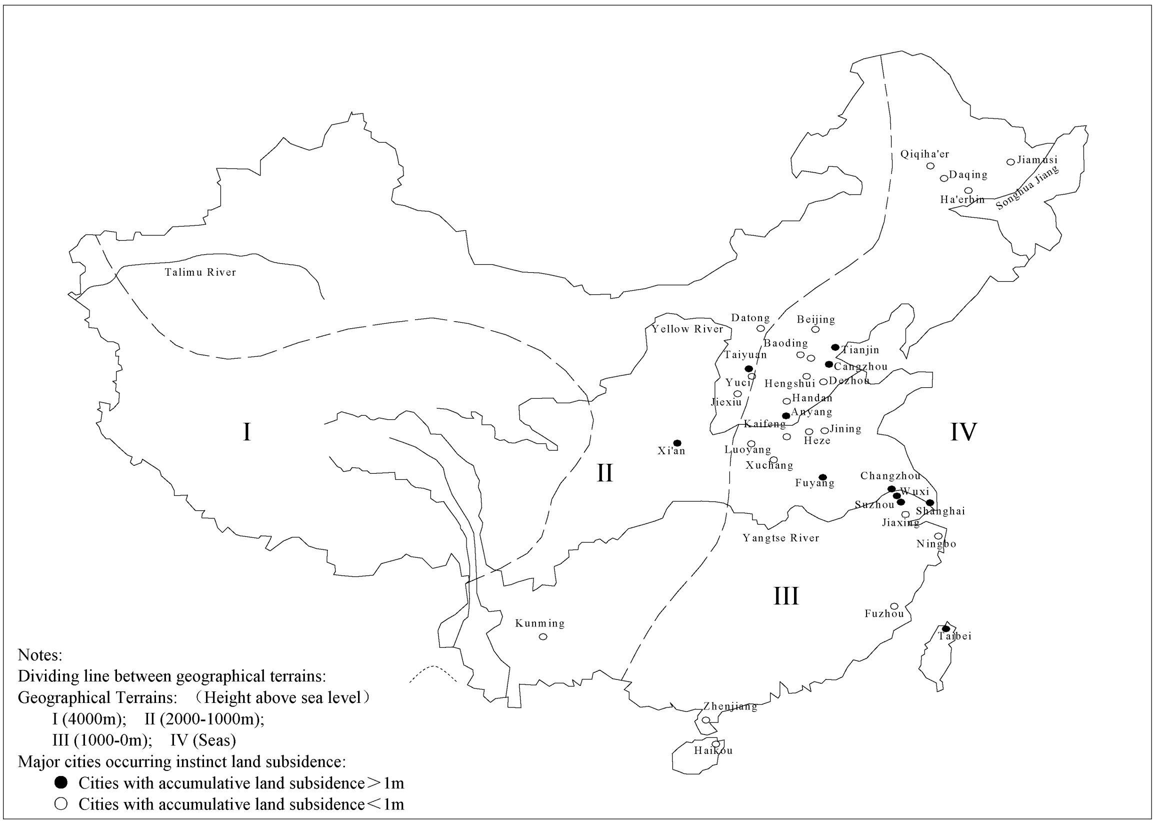

Figure 1. Geographical distribution of major cities where substantial land subsidence is occurring

At present, China has 95 cities and municipalities where disastrous land subsidence has occurred or is occurring. The statuses of some of the subsidences are briefly summarized in Table 2. The total subsidence area is about 49,000 km^2 (Duan 1993, 1998). It is roughly estimated that the annual economic loss due to subsidence is greater than one hundred million. At present, more than 11 cities have had an accumulative subsidence of greater than 1 metre at their subsidence centres. These cities include Shanghai, Tianjin, Suzhou, Wuxi, Changzhou, Cangzhou, Xian, Fuyang, Taiyuan, Anyang and Taibei.

Investigations have shown that the land subsidences in China have been caused primarily by increasing withdrawal of groundwater from various depths. This cause is clearly reflected by the distribution pattern of cities with noticeable subsidence (Fig.1). The subsidence-affected cities are also those, which over the last four decades have undergone rapid expansion and the development of industrialization and urbanization. The main features of the land subsidence in China are given below.

Migration of subsidence areas from exiting industrial cities to emerging industrial cities

Land subsidence in China was initially recorded in Shanghai and Tianjin during the 1960s. Shanghai and Tianjin were the two largest industrial cities in China and the government carried out substantial preventive and remedial measures to control the subsidence. Currently, these initial land subsidence areas are basically controlled. Field measurements indicate that these initial subsidence areas are now experiencing little subsidence and in the case of Shanghai, it is in a state of rebound (Liu 1998a). Tianjin implemented the first subsidence-monitoring project in 1986 and the land subsidence was also basically controlled as well. The average annual subsidence always fluctuates around

14mm a year (Hu 2002) and the entire Tianjin region has shown a small amount of subsidence each year since 1986 (Figure 2).

In contrast, many median-size emerging industrial cities such as Cangzhou, Suzhou, Wuxi, Changzhou, Fuyang and An'yang are in the initial state of rapid land subsidence development. The annual subsidence rate can be between 50 to 100 mm (Duan 1993, 1998). The land subsidence in these cities is expected to continue and increase due mainly to the rapid industrial and urban expansion that is expected to continue for another decade.

Table 2. Summary of the land subsidence conditions in major cities of China (after Duan 1998)

Shanghai	850	The land subsidence began in 1920. The most serious subsidence occurred in 1964. The maximum subsidence is 2.63 m. The subsidence has been gradually controlled. At present, the ground surface is at a state of minor fluctuation of subsidence and rebound.
Tianjin	10000	Since 1959, subsidence has been occurring on the plain with an area of 10000 km^2. The centre of Tianjin, Tanggu and Hangu are the three subsidence centers. The maximum subsidence is 3.06 m and the subsidence rate 160 mm/a. At present, the averaged subsidence rate between 8 to 56 mm/a.
Suzhou Wuxi Changzhou	380	Subsidence appeared in 1960. The cumulative subsidence amounts for each town are 1.1, 1.05, and 0.9 m and the present maximum subsidence rates are 40 to 50, 15 to 25, and 40 to 50 mm/a, respectively.
Ningbo Jiaxing	263	The maximum accumulative subsidence amounts are 0.346 and 0.597 m, respectively from 1960 to 1989. The present maximum subsidence rates are 18 and 41.9 mm/a.
Heze Jining Dezhou	53	Subsidence appeared in 1978, 1988 and 1978 respectively, the accumulative subsidence are 0.07,0.063 and 0.104 m, the maximum subsidence rate are 9.68, 31.5, 20 mm/a, respectively.
Xi'an	250	Seven subsidence centres have appeared since the 1950s, the maximum accumulative subsidence is 1.9m, the maximum subsidence rate 136 mm/a.
Xuchang Kaifeng Luoyang An'yang	59	Subsidence appeared in 1985, 1979 and 1979 and the maximum subsidence amount is 0.208, 0.21, 0.113, 0.337 m, respectively. An'yang suffered regional subsidence with a rate of about 65 mm/a.
10 cities in Hebei Province	36000	Subsidence started in the 1950s on Hebei plain and formed 10 subsidence centers: Cangtzhou, Hengshui, Renqiu, Hejian, Bazhou, Baoding, Dacheng, Nangong, Feixiang, Handan. The maximum accumulative subsidence is 1.131m and rate is 96.8mm/a.
Fuyang	360	Subsidence appeared in 1970, the maximum accumulative subsidence was 1.02 m in 1992 and the rate is 60-110 mm/a.
Ha'erbing Daqing Qiqiha'er Jiamusi	?	Building crack and land deformation occurred in 1974. The cause was large scale groundwater withdrawal. In Ha'erbing and Daqing, the areas of lowed ground water level are 258km^2 and 4000km^2 respectively, and the maximum accumulative depressed depths of water table are 26.85m and 20-30m respectively.
Taiyuan Datong Yu'ci Jiexiu	200	Subsidence appeared in Taiyuan in 1979 and Datong in 1988. In Taiyuan, the subsidence is 1.967 m and the rate is 0.037 – 0.114 mm/a. In Datong,Yu'ci and Jiexiu, the subsidence rates are 31,10-20,5-7.5 mm/a, respectively. Without elevation measurement, the subsidence amounts in these cities have been unknown.
Beijing	314	Subsidence started at end of 1950s. The maximum accumulative subsidence is 0.597 m.
Kunming	?	Subsidence appeared at the east railway in Kunming. Without monitoring data, the subsidence amount is unknown.
Zhanjiang	0.25	Subsidence appeared in 1960s. Accumulative subsidence is 0.11 m. Subsidence has been controlled basically because of decreasing groundwater withdrawal.
Haikou	?	Subsidence was observed about 0.07m in 1990s. At present, subsidence is small.
Fuzhou	9	Subsidence appeared 1957, the accumulative subsidence is 0.68 m, the rate 2.9 to 21.8 mm/a.
Summary	48728	39 cities suffered land subsidence in China. They are located in Yangtze River Delta Plain, Hebei Plain, Southeast China, Huanghe River Plain and mountain basins. The direct economic loss up to 1997 is estimated at over RMB$ 100 million.

Figure 2. Variation of the annual land subsidence from 1959 to 1997 at BM Bu 435 (a long-term monitoring point in Tanggu, Tianjin)

Migration of subsidence centres from existing city centres to surrounding newly urbanized areas

The centres of many cities in China are usually the areas with the densest population and the highest concentrations of industries. They are also the areas with the greatest amounts of groundwater withdrawal. Therefore, land subsidence in each city has usually commenced in the centre. In recent years, the implementation of groundwater abstraction controls in city centre areas has significantly reduced the subsidence rate.

In contrast with this, the industrializing cities have rapidly urbanized their surrounding rural areas with many new factory developments. Groundwater withdrawal in the newly urbanized areas is becoming substantial, but there are no effective measures to control this groundwater use. Consequently, land subsidence has increased remarkably and the subsidence rates are high. For example, in Tianjin, land subsidence started in 1959 and has a maximum accumulative subsidence of 2.8 m with an average annual subsidence rate of 66.67 mm (Cui, 1998). By comparison, in the Tanggu area a suburb county of Tianjin, the land subsidence started in 1960 and has the maximum accumulative subsidence of 3.06m. Here the average annual subsidence rate is 75 mm, which is greater than the average annual subsidence rate in the central Tianjin; Tanggu has become the new subsidence center (Hu, 2002). In addition, the annual subsidence rate in another suburb county Hangu, was 56 mm. Since 1982 Tanggu has implemented some measures to control subsidence and the present annual subsidence rate has been reduced to about 20 mm.

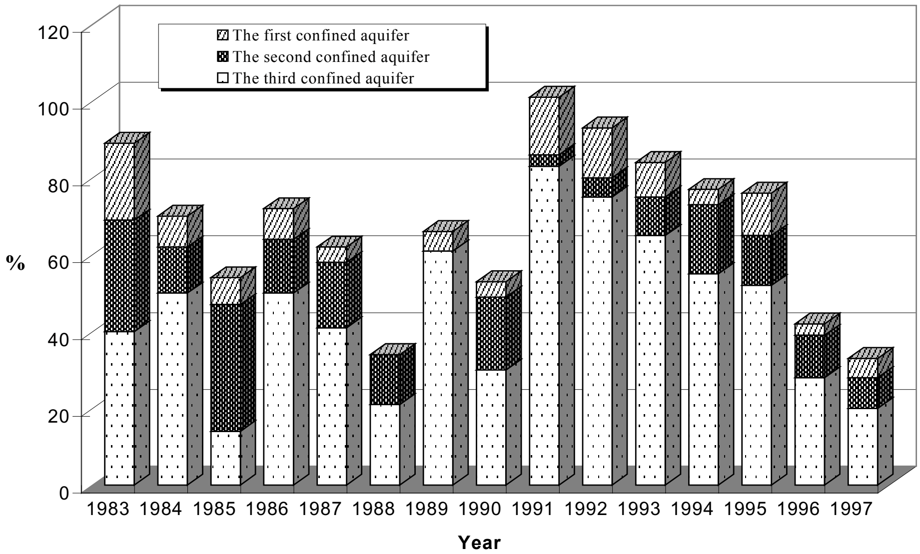

Figure 3. Percentage contributions of the deformation from three shallow confined aquifers to the total subsidence at Alkali Mill in Tianjin

Table 3. The features of the subsiding strata in Tianjin (1995 data)

Geological age		Depth of base (m)	Thickness (m)	Genesis	Lithological characters	Aquifer group	Depth of ground water table(m)	Lithological unit	Water content (%)	Density (g/cm^3)	Void ratio	Liquid index	Compressive index	Consolidated status
Holocene	Q_4^3	5-6	5-6	Flood-plain	Upper: Fills Lower: Brown loams or clays	Phreatic water	1-2	1	32.5	1.91	0.90	0.71	0.237	Over-consolidation
	Q_4^2	14-16	10-11	Shallow sea	Gray loam intersected with silts	Slightly confined aquifer		2	30-42.2	1.7-1.9	0.8-1.2	0.8-1.1	0.227	Normal consolidation
	Q_4^1	20-23	5-7	Flood-plain	Brown loams			3	25-32.3	1.92-2.07	0.6-0.8	0.5-0.7	0.172	Normal consolidation
Late Pleistocene	Q_3^3	50-60	27-38	Intersecting sea and land	Gray-brown loams, clays intersected with silts	The 1st confined aquifer	6-7	4	23.5-30.2	1.95-2.03	0.5-0.7	0.2-0.5	0.165	Slight over consolidation
	Q_3^2	70-80	15-20	Flood-plain	Brown clay, loam	The 2nd confined aquifer	20-30	5	23.5-30.0	1.95-2.11	0.5-0.7	0.29-0.5	0.185	Over-consolidation
		120-130	50	Land with a little sea	Dark green-brown loam, clay and silt			6	23.0-30.0	1.94-2.14	0.5-0.78	0.3-0.65	0.204	Over-consolidation
	Q_3^1	170-180	40-50	Land	Dark green-brown clay, loam and silt			7	17-25.0	1.96-2.07	0.5-0.73	0.1-0.5	0.232	Over-consolidation
Middle Pleistocene	Q_2^2	270-327	100-140	Lake	Light brown clay, loam intersected with silt	The 3th confined aquifer	40	8	22.0	2.03	0.606	-0.128	0.190	Normal consolidation
	Q_2^1	383-404	77-121	River and lake	Brown or dark-green clay, silt and moderately-coarse sand	The 4th confined aquifer	40-70	9	18.6	2.13	0.525	-0.3	0.170	Normal consolidation
Early Pleistocene	Q_1	530-550	147-156	River and lake	Brown clay and fine sand	The 5th confined aquifer	60-70	10	21.1	2.10	0.589	-0.065		Normal consolidation
Pliocene	N				Brown or dark yellow clay, loam and silt		60-80	11	20-22.0	2.06-2.13	0.57-0.62	-0.14-0.49		Normal consolidation

Migration of settlement strata from shallow to deep depths

Figure 3 shows the annual variations of deformation (as a percentage) contributed by the three confined acuifers (from shallow to deep) to the total subsidence in Tianjin. The data were observed by seven wire-flex extensometers at the Tianjin Alkali Mill. As shown in Figure 3 and Table 3, the soil strata depths increase from the first layer to the third layer of the aquifer groups in the ground, and their lithological characters are dominated by clays and loams (Table 4). Most of groundwater aquifers are confined and groundwater exploitation is chiefly located in the 2nd and 3rd aquifers; the thermal water is stored in Pliocene strata.

The results in Figure 3 clearly indicate that the contribution from the third aquifer stratum to the total subsidence has been generally the greatest over the past 15 years. The contribution from the second aquifer group has been the second. The contribution from the first aquifer group has been the third.

Over eleven years, the percentage of water taken from the third aquifer group has been increasing. The percentage contribution from the first aquifer group has been attenuating. Consequently, the dominant stratum on which settlement has occurred has transferred to a deeper location. This observation is consistent with the fact that water or hot water has been withdrawn from deeper and deeper ground over the years. Hence, the deep soil strata will continue to contribute a much greater percentage to land subsidence at the ground surface. Therefore, a more effective measure to control land subsidence would be the treatment and remediation in deep soil layers. It is noted that the above phenomenon can also be seen in Shanghai (Liu 1998a, Yan & Liu 1996).

Table 4. Details of main aquifers in Tanggu, Tianjin City,China

	Name of aquiders	Dominated lithology	Depth of bottom (m)	Thick-ness (m)	Water table				Degree of mineralization (g/l)
					Depth of water head (m)	Period for high water table	Period for low water table	Annual change (m)	
A	Phreatic aquifer	yellow-grey porous clay and lens-shaped silts	4-6	4-6	Shallow	Vary with the seasons			1-2
B	Slightly confined aquifer	lens-shaped silt and fine sands	15-20	9-16	1.5-5.0				2-6
C	First confined aquifer	silt and fine sands	60-75	40-60	6-15	Jun - Sept.	Nov. - Mar.	1-5	10-15
D	Second confined aquifer	silt and fine sands	170-190	25-60	15-20		Jun. - Aug.	4-8	Upper: salt Bottom: fresh
E	Third confined aquifer	silt and fine sands	270-310	30-55	45-65		Jun. - Aug.	1-4	0.5
F	Fourth confined aquifer	Fine sands, silt	370-400	30-50					0.4-0.6
G	Fifth confined aquifer	Fine sands, silt	About 550	20-30	70-80				0.34-0.43

Occurrence of severe subsidence in great Yangtze River Mouth Delta

Shanghai, Suzhou, Wuxi, Changzhou and Hangjia Lake are situated in the southern part of Yangtze River Mouth Delta region. They cover an area of 30,000 km^2 (about 0.3 % of the total national territory) and form one of the most industrialized areas of China. Their contribution to the gross national product is about 15.3 % (Duan *et al*. 1993). Due to the high-speed development in those cites, land subsidence here has been the most common and serious environmental geological problem, which is discussed below.

In recent years, the development of disastrous land subsidence in Suzhou, Wuxi and Changzhou cities and in Hangjia Lake has been more rapid than that in Shanghai. Generally in the world, it has been reported that visible land subsidence is not be observed within 30 years of the withdrawal of either oil or ground water. In Shanghai, the visible land subsidence was observed after about 35 years of groundwater withdrawal for industrial use (Liu 1998b). In the three cities of Suzhou, Wuxi and Changzhou and in Hangjia Lake, evident land subsidence was observed within 30 years of industrialization from 1960 to 1990s (Duan 1993).

Cracks in the ground have appeared in this area, they started in Hetang County, Jiangyin, and formed from the end of 1995 to the beginning of 1996. The cracks were up to 450 m long, 36 cm wide and 6 to 9 m deep (Zhu and Zhu, 1998).

Flooding is also a threat to these cities. Since the ground elevation in these areas is only about 23 m, the floodgate breakwater dams around Tai Lake are too low to hold back the flood at the 3.5m flood-warning water level. Shanghai is also similarly affected by the storm tides (Zhou 1998).

The land subsidence that affects the cities of the Yangtze River Mouth Delta has common geological conditions. All thee areas belong to the same deltaic geological unit, have the same hydro-geological conditions and a unified groundwater system. The controlling hydrological unit is the Tai Lake, which causes the flood problem. Because three provincial governments administer the cities, it is easy to observe the differences in the way they deal with the problems. There are inconsistencies in management, monitoring, investigation and the control of both land subsidence and groundwater withdrawal.

SUBSIDENCE PREVENTIVE AND REMEDIATION MEASURES

Preventive measures for land subsidence in China include four main aspects: a) disaster management measures, b) depth-controlling measures, c) monitoring measures and d) administrative regulation measures. The disaster management measures include the construction of flood-proof walls and pumping stations to dewater waterlogged areas in urban districts. The depth-controlling measures include the control of the following activities related to groundwater use: groundwater withdrawal; artificial groundwater recharge; changing groundwater withdrawal layers; and setting up the annual programme and schedules for the withdrawal and recharge of groundwater. The monitoring measures include: levelling of land surveying benchmarks; measurement of wire-flex extensometers; long-term observation of groundwater variations and fluctuation; hydrologic and geologic investigations.

CONCLUSIONS

Industrialization and urbanization have occurred rapidly in many regions and areas in China, this trend is expected to continue for the next two decades. Consequently, the groundwater resources in China will be used at an accelerated rate in order to meet the demands of the increasing population and industrial development. Land subsidence is likely to continue in those cities listed in Table 2 and to occur in many other cities. The prevention of land subsidence and minimization of the hazards induced by it will continue to be a challenging task facing the governments, engineering geologists and geotechnical engineers.

Since 1991, land subsidence has continued as one of the UNESCO's IHP-IV projects "Ground Water Assessment and Environmental Impact due to Over-development-Land Subsidence." Since 1969, UNESCO has organized a number of symposia and conferences on the subject of land subsidence around the world, except in China. It is therefore recommended that, in the near future, the next International Symposium on Land Subsidence should be organized in China. It is believed that organization of such a symposium in China would definitely benefit the sustainable economic development and environment in China and around the world.

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