

Large differential land subsidence and earth fissures in Jiangyin, China

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Abstract Jiangyin County is in the infamous Su–Xi–Chang land subsidence area caused by excessive groundwater withdrawal in Jiangsu province, China. The maximum accumulated land subsidence reached 1,310 mm near the centre of the subsiding trough in 2006 in southern Jiangyin, and earth fissures of significant vertical offsets have been observed at Changjing, Hetang and Wenlin which form an arc towards the subsidence trough. An ancient Yangtze River course is found underlying and passing through the depression in southern Jiangyin, forming a local basin surrounded by outcropped bedrock ridges in the north and south. The Quaternary stratigraphy demonstrates significant heterogeneities in the basin; the second confined aquifer is much thicker and deeper and encapsulated inside the basin and absent above the ridges. The development of earth fissures along the Changjing–Hetang–Wenlin arc might be a combination of an inward rotation of sediments due to a large differential subsidence, an inward movement driven by seepage force and a steeper slope along the south-eastern shoulder of the basin that facilitates the development of horizontal tensile strain and/or shear strain necessary for fissuring. The land subsidence has slowed down and no new earth fissure zone has

occurred in the area after the banning of deep groundwater extraction was enacted in 2001.

Keywords Differential land subsidence · Earth fissure · Groundwater depletion · Jiangyin · Su–Xi–Chang area

Introduction

Land subsidence due to groundwater depletion can cause environmental and/or economic impacts (Bouwer 1977; Holzer and Johnson 1985; Abidin et al. 2001; Phien-wej et al. 2006; Wang et al. 2009d), including earth fissures or ground cracks. In China, Suzhou–Wuxi–Changzhou (Su–Xi–Chang) area has the most serious land subsidence due to excessive groundwater extraction from the Quaternary aquifers (Wang 1998; Chen et al. 2003; Shi et al. 2007; Zhang et al. 2007a; Shi et al. 2008; Wang et al. 2009d). The maximum accumulated land subsidence reached 1,187 mm between 1980 and 1997 in Suzhou City (Chen et al. 2003) and increased to 1,664 mm in 2001, more than 1,924 mm by 2000 in Wuxi City (Wang et al. 2009a) and 1,800 mm by 2002 in Changzhou City (Wang et al. 2009d). The area of land subsidence in this region has dramatically expanded and has exceeded 10,000 km² (Zhang et al. 2007b; Shi et al. 2008). Furthermore, earth fissures are widely spread and scattered mainly in the west of Wuxi city, Jiangyin county and Wujin county (Wang et al. 2009c). The first earth fissure was reported in 1989 in Henglin town, 18 km southeast of Changzhou City (Zhang et al. 2007a). Earth fissures and house damages at Dongting town, Wuxi city, have forced the terrified villagers to leave their houses since 1990 (Zhu et al. 1993). Between 1994 and 1998, five earth fissures occurred in western Wuxi city (Hu and Wu 1998). The causative mechanisms of earth

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fissures in Su–Xi–Chang area were summarized as bedrock ridges and cliffs, karst of shallow limestone and alteration of the Quaternary strata (Yu et al. 2004). Wang et al. (2009c) reported earth fissures triggered by excessive groundwater withdrawal and coupled by geological structures in Jiangsu, including several cases in Su–Xi–Chang area.

The impacts of land subsidence observed in this area include well protrusion, earth fissures, decreasing clearance beneath bridges, increased flood threats and damages to the national survey marks, infrastructures, farms and buildings (Wang et al. 2009c; Wang et al. 2009d). Jiangsu provincial government enforced restrictions on groundwater withdrawal in 1995 to reduce the land subsidence and its impacts, but the scale and magnitude of land subsidence has still rapidly increased. The government further enacted a total ban on deep groundwater extraction in 2000 in Su–Xi–Chang area for 5 years, aiming to mitigate geohazards from the land subsidence and earth fissures and to conserve the groundwater resource. As a result, the groundwater level is gradually recovering, the land subsidence is slowing and no new earth fissure is occurring.

Jiangyin County is within the infamous Su–Xi–Chang land subsidence area caused by groundwater depletion. However, the land subsidence in southern Jiangyin features a large differential land subsidence in a short distance (more than 1,000 mm in 1 km) and a high frequency of occurrence of earth fissures with an apparent vertical offset. These features have led to investigations on the effect of a buried ancient Yangtze River course passing southern Jiangyin. As this special hydrogeological structure is present in a large part of Su–Xi–Chang area, it is significant to study the mechanism of large differential land subsidence and earth fissures in southern Jiangyin to construct a representative “Visualized Three Dimensional Geological Model of Land Subsidence in Su–Xi–Chang Area”, which is a part of the “Geological Investigation and Monitoring of Jiangsu Province Environmental Ecosystem” project in Jiangsu, China.

Geological and hydrogeological background

Jiangyin is a famous county whose economy has ranked number one among counties in China for consecutive 6 years. The land area is 987.5 km², the population was 1,197,700 and the GDP was about 119 billion Chinese Yuan in 2007. Jiangyin is a part of the Great Yangtze Delta and Taihu Lake Quaternary alluvial sedimentary plain, which is flat with an elevation of 3–6 m above the sea level. Figure 1 shows the study area marked as a rectangle in the centre of the Great Yangtze River Delta. The study area is about 25 km east of Changzhou city and

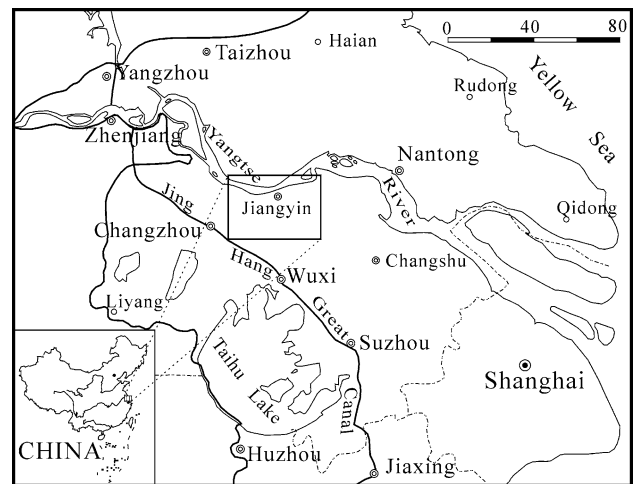


Fig. 1 Location of the study area on the Great Yangtze River Delta

about 15 km north of Wuxi city. Yangtze River is in the north of the study area and Jing Hang Great Canal in the south which connects Changzhou, Wuxi and Suzhou cities.

Figure 2 is the geological sketch in Jiangyin where the solid line is the bedrock contour below the ground surface. The geological structure features Shengang and Qingyang depressions and a series of residual bedrock ridges striking at NE and NEE north of Nanzha–Yunting–Huaxi and along Yanqiao–Wenlin and Gushan in the south. The Qingyang depression in southern Jiangyin is filled with Quaternary sediments; underneath is a buried course of the ancient Yangtze River whose boundaries are the dotted lines in Fig. 2; the Quaternary is thicker in the centre and gradually becomes thinner towards the ancient river banks, typically ranging from 120 to 180 m. There is a local bedrock basin around Changling, Hetang, Wenlin, Mazhen, Xuxi, Zhutang and Luqiao in the research area.

Illustrated in Fig. 3 are the geological cross sections, AA' in the Shengang depression and BB' and CC' in the southern basin. The stratigraphy demonstrates significant heterogeneities. In general, there are four aquifers: one unconfined aquifer and three confined aquifers, which are denoted as UCA, CA1, 2 and 3. UCA consists of alluvial silty clay and silt, and its groundwater level is 1–3 m below the ground surface. The pumping yield of a single well is generally less than 10 m³/day from UCA, but it may be greater than 10 m³/day near the Yangtze River in the Shengang depression. CA1 consists of one to three sand layers, the sand can be silty sand, fine sand and/or silt, the groundwater level in CA1 is generally 5–10 m below the ground surface and 10–18 m in pumping areas, and the pumping yield of a single well is 100–500 m³/day from CA1. UCA and CA1 may be connected due to the discontinuous aquitard in-between.

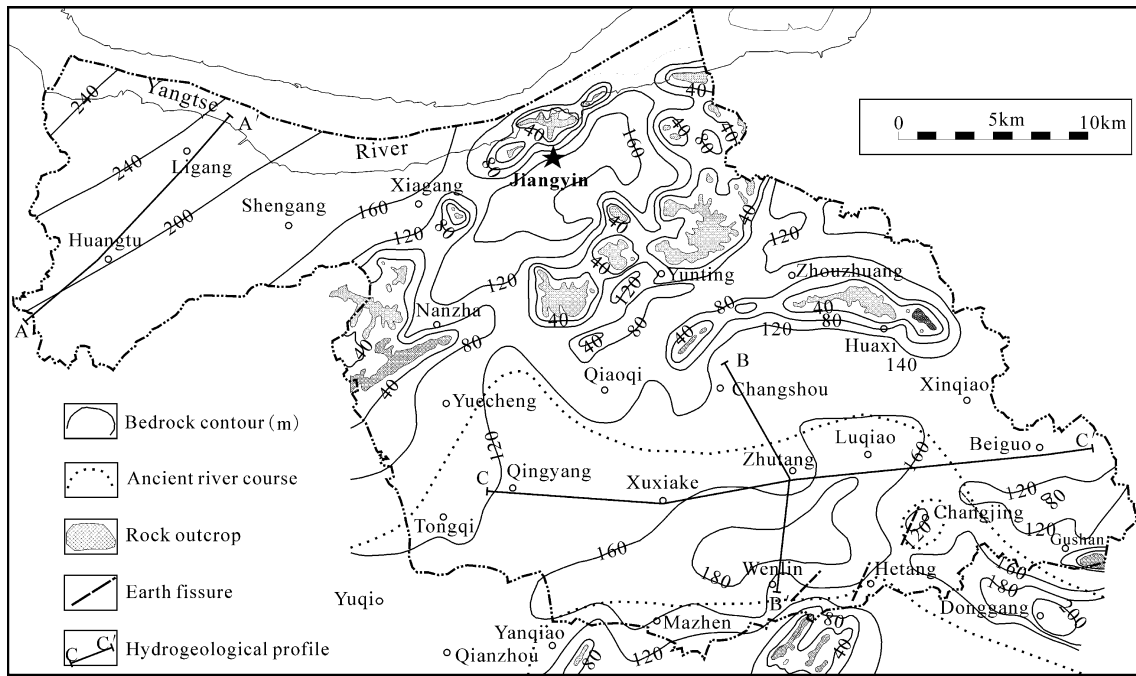


Fig. 2 Sketch of geological map of Jiangyin, China

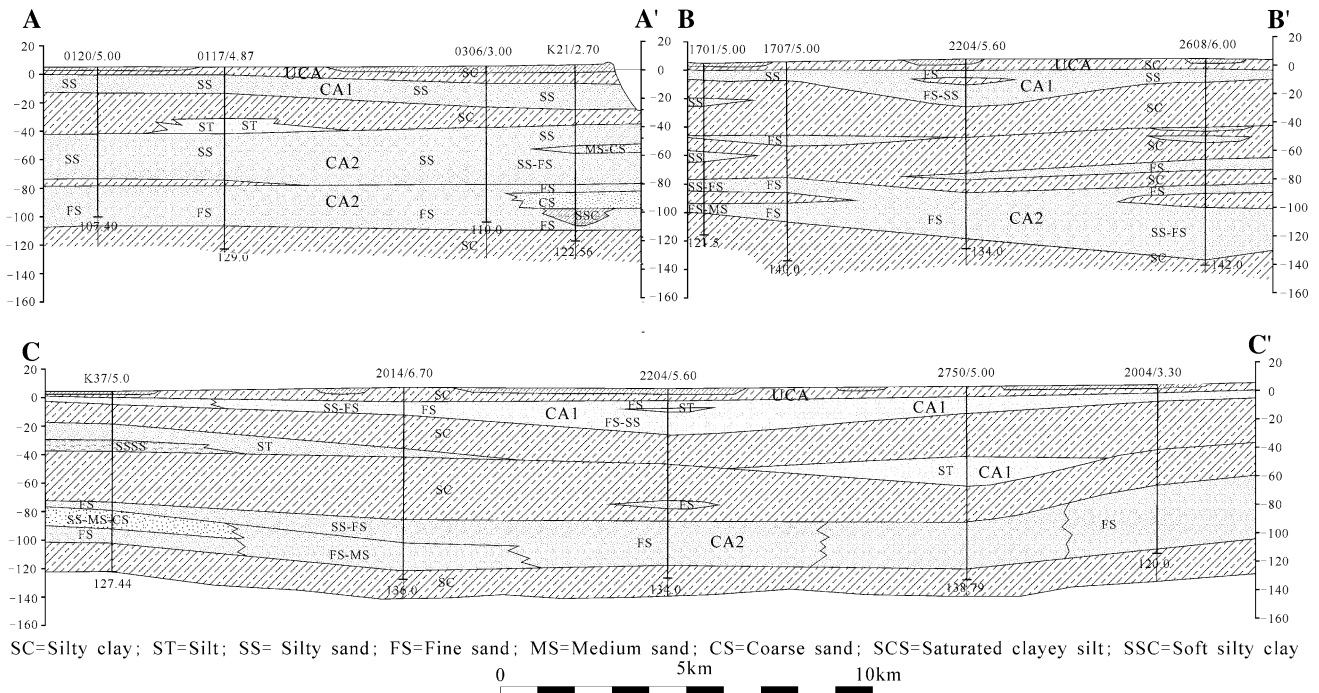


Fig. 3 Hydrogeological cross sections of Quaternary sediments in Jiangyin

CA2 is the major aquifer for groundwater extraction in the region. Controlled by the underlying geological structure, the depth, thickness and soil and hydraulic properties of CA2 are heterogeneous and/or anisotropic. The sand layer is thicker at the centre of the ancient river course and thinner towards both sides and gradually disappearing at

the ridges and/or cliffs. The stratum consists mainly of alluvial medium to fine sand and silty sand with some silt and silty clay seams. Its thickness varies from 15 to 38 m; it is more than 30 m thick at Xuxiake, Zhutang, Changjing and Beiguo and less than 20 m north of the Yuecheng–Changshou–Huaxi line and south of the Mazhen–Wenlin

line. In contrast, it is 39–68 m in the northwest, becomes gradually thicker from south to north and thicker than 70 m at Shengang. The depth is generally 64–102 m in the south, more than 90 m at Xuxiake, Zhutang, Luqiao and Changjing, less than 80 m north of the Qingyang–Changshou line and south of the Wenlin–Hetang line, gradually decreasing to 70 m east of Changjing. On the other hand, it is 37–48 m deep in the northwest, deeper than 45 m south of the Huangtu–Shengang–Xiangang line, becoming gradually shallower to north and less than 40 m from Ligang to the river bank, where CA2 locally connects with CA1. The hydraulic conductivity is higher at the centre of the basin and gradually decreases towards the surrounding bedrock ridges in the south. It is greater than 10 m/day at Qingyang, Xuxiake, Zhutang and Luqiao, less than 5 m/day at Nanzha, Qiaoqi, Changshou and Huaxi and south of the Wenlin–Hetang line, and 5–10 m/day for the area in-between. It increases from south to north in the Shengang depression; it is less than 5 m/day south of the Huangtu–Shengang–Xiangang line and more than 10 m/day north of the Shizhuang–Ligang line. In CA2, the pumping yield of a single well in the northwest is more than 2,000 m³/day north of the Huangtu–Shengang–Xiangang line and 1,000–2,000 m³/day south of this line, and more than 3,000 m³/day from the Shizhuang–Ligang line to the river bank. It is typically 1,000–2,000 m³/day in the south. As CA2 is overlain by a clay layer, CA2 is encapsulated and the recharge to CA2 is poor.

The sediment in CA3 is mainly fine to medium sand; CA3 is absent in most southern area, with a local presence at Zhutang. Its depth is 114–145 m. The thickness ranges from 14 to 100 m, 14 m at Xiangang and about 50 m in the Huangtu–Shengang area. The thickest zone is from the north of Ligang to the river bank. The pumping yield of a single well is more than 2,000 m³/day at Ligang, 1,000–2,000 m³/day at Shizhuang and less than 1,000 m³/day in the Shengang–Xiangang area. The groundwater level in CA3 is slightly higher than that in CA2.

Groundwater exploitation

Groundwater exploitation in southern Jiangyin started in the 1980s, the extraction rate was low, and the groundwater level was generally within 20 m from the ground surface. It is believed that the original groundwater levels in all aquifers were about the same and near the ground surface in this region (Li et al. 2006). With a rapid development of the local economy and urbanization, the surface water became severely polluted in southern Jiangyin, so deep groundwater was exploited at an ever increasing scale. Especially in the 1990s, groundwater extraction was dramatically expanded, so the groundwater level rapidly

declined in CA2. The groundwater extraction peaked in the middle 1990s, so did the groundwater drawdown. The groundwater drawdown was more than 3 m/year in most areas in the south. For example, the groundwater level declined from 34 m in 1988 to 63.3 m in 1997 at a chemical plant at Hetang, or an average drawdown of 3.26 m/year, and from 32.5 m in 1992 to 63.53 m in 1997 at Xinqiao, or an average drawdown of 6.21 m/year. This indicates that the groundwater in CA2 was severely overdrawn. As a consequence, the cone of depression in CA2 continuously enlarged, leading to land subsidence, earth fissures and other environmental geological problems.

Since 1995, the government has strengthened restrictions on groundwater extraction, and some deep wells have been sealed. The effect of this enforcement has manifested in the decline of extraction rates as shown in Fig. 4. Consequently, the groundwater level has gradually recovered. Shown in Fig. 5 is the groundwater level below ground surface from 1999 to 2007 at Changjing, Hetang, Qingyang, Xinqiao and Zhutang in the area, which all presented a rise. In particular, the groundwater level rose from 55 m below ground surface to 25 m at Zhutang.

In 1997, the groundwater level in CA2 was more than 60 m deep in most areas, the lowest was 75 m at the cone centre in the area of Tongqi and Mazhen which was affected by a underground mining in the proximity, and it recovered to the 40 m level east of Changjing.

In 2001, the regulation on deep groundwater extraction was further tightened from restriction to prohibition. From 2001 to 2005, 460 deep wells were sealed, and the groundwater extraction through deep wells was completely stopped in 2005 in contrast to the rate of 29,000,000 m³ in 2000. The groundwater level began to recover slowly since CA2 is encapsulated with a poor recharge. However, the enforcement of prohibition is a turning point to reverse the worsened geological environment. The recovery of groundwater in CA2 is significant: the areas within the 60,

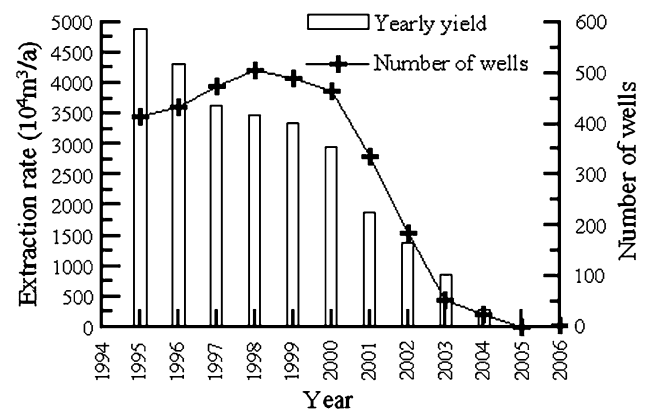


Fig. 4 Groundwater extraction rate and wells between 1994 and 2006 in southern Jiangyin modified from (Wang et al. 2009b)

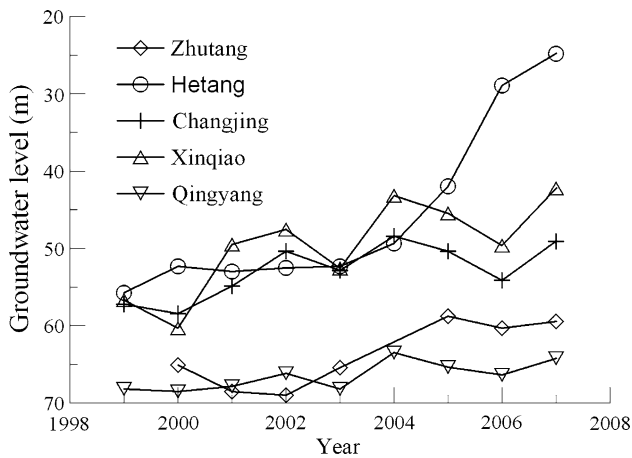


Fig. 5 Groundwater recovery in Jiangyin from 1999 to 2007

50 and 40 m groundwater level contours over the cone of depression decreased from 272, 433 and 535 km² in 2000 to 118, 309 and 407 km² in 2006, respectively (see Fig. 6).

Land subsidence

Land subsidence in Jiangyin County started in the early 1980s when the subsidence rate was within 15 mm/year. The land subsidence rate then accelerated in accordance with the expansion of the cone of depression caused by the

dramatic groundwater drawdown. It exceeded 100 mm/year in 1994 in many towns in the basin, the cone of depression further expanded and merged with the Wuxi regional cone of depression, and the accumulated land subsidence generally exceeded 600 mm. The groundwater extraction declined after the implementation of restrictions in 1995, but the subsidence rate remained at 80 mm/year. By 2000, the land subsidence exceeded 1,000 mm in Qingyang, Xuxiake and Mazhen and the rate was about 50 mm/year. The area where land subsidence exceeds 800 mm is more than 200 km² in the southern Qingyang depression, but the accumulated land subsidence is not more than 200 mm in the northwest Shengang depression.

After the enforcement of banning groundwater withdrawal through deep wells in 2001, the land subsidence rate has greatly decreased as demonstrated in Fig. 7 which depicts the land subsidence rate from 1984 to 2004 at the local trough centre between Mazhen and Xuxiake, the land subsidence between 1980 and 2006 at Mazhen monitoring benchmark (BM1 in Figs. 6, 7) and the land subsidence between 2003 and 2006 at Xuxiake extensometer station that was installed in bedrock (BM2 in Figs. 6, 7). The land subsidence rate in southern Jiangyin has declined to 10–20 mm/year from 110 mm/year in 1994 as shown by the column chart in Fig. 7. On the other hand, the land subsidence is negligible north of Nanzha–Yunting–Huaxi and is less than 200 mm in the Shengang depression and around the ridges in the south (see Fig. 6).

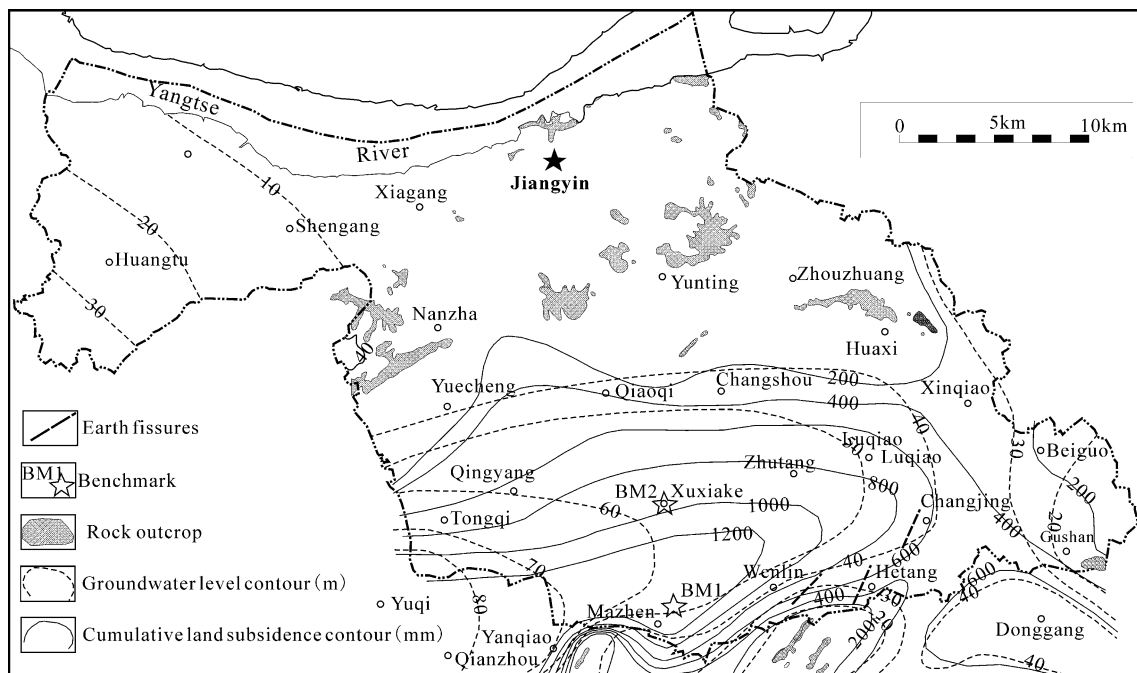


Fig. 6 Contours of land subsidence and groundwater level in CA2 in Jiangyin in 2006

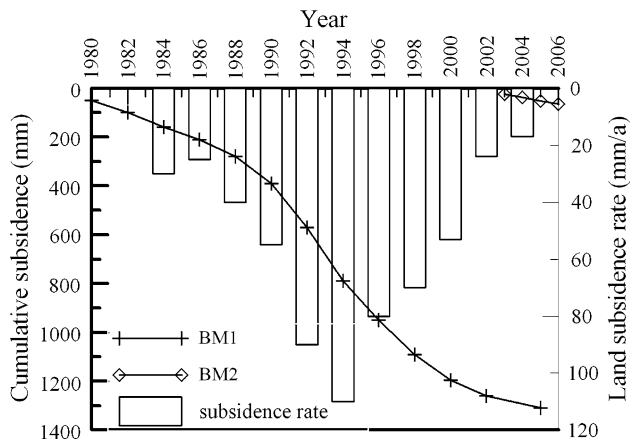


Fig. 7 Accumulated land subsidence and subsidence rate in southern Jiangyin modified from (Wang et al. 2009b)

Earth fissures

Changjing, Hetang and Wenlin earth fissures started in 1997, 1995 and 2001, respectively in southern Jiangyin. These earth fissures caused damage to buildings, roads and farmland. Figure 8a demonstrates a severe building crack at Changjing, Fig. 8b is cracks in a concrete pavement at Hetang and Fig. 8c is a fissure on a slab and a house at Wenlin. Hetang and Changjing earth fissures have been investigated through a range of means, including shallow seismic survey and geological drilling. The results of the investigations have been reported previously (Wang et al. 2009c). Figure 9 presents the latest development of the vertical offsets measured at Hetang and Changjing earth fissures. The offsets developed mainly before 2000 and appeared steady from 2002 to 2004. However, two leveling surveys conducted in 2006 and 2007 suggest that they are still active and that the differential settlement rate may reach 5.0 mm/year in some sections, implying the consolidation and/or compaction of the aquifer system are not complete.

Wenlin earth fissure was first observed in 2001 and accelerated in 2002. The main fissure appears as a scarp with the NW side offset downwards 100–150 mm, forming a depressed strip of 20 m wide adjacent to the scarp on the NW side. There are a number of secondary earth fissures in the strip, which are parallel to the main fissure. Wenlin earth fissure is 300 m long and trends NE45°. This earth fissure resulted in ten houses damaged and six of them demolished.

Discussion and conceptual model

Overdraft of groundwater from an aquifer may disturb the existing hydraulic balance between discharge and recharge.

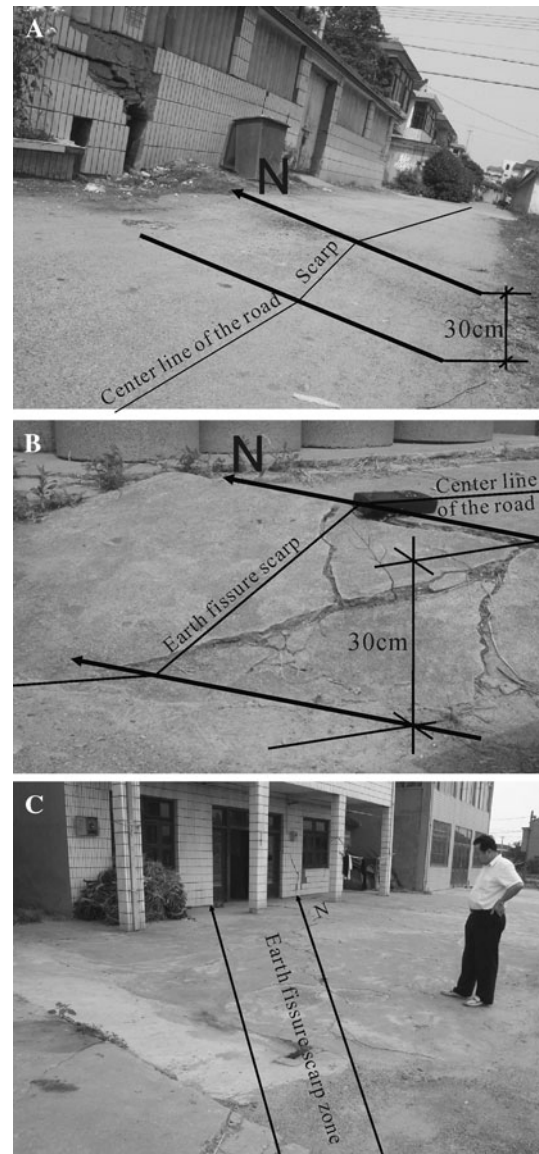


Fig. 8 Photographs of Changjing, Hetang and Wenlin Earth Fissures

As it may have to flow through the aquitard superjacent to the aquifer, the recharge may be impossible to immediately compensate the depletion of groundwater due to pumping, resulting in a rapid drawdown of groundwater. Such a drawdown leads to the increase of effective stresses in the aquifer and aquitard strata. Therefore, the consolidation theory is applied to explain the land subsidence caused by groundwater depletion. One dimensional consolidation is generally used in literature (Bouwer 1977; Rojas et al. 2002; Chen et al. 2003) probably due to its simplicity and the fact that land subsidence caused by groundwater depletion generally occurs in large alluvial deltas, plains or basins (Xu et al. 2008). Theoretically, the long term land subsidence in this context consists of three stages, namely elastic deformation, primary and secondary consolidations.

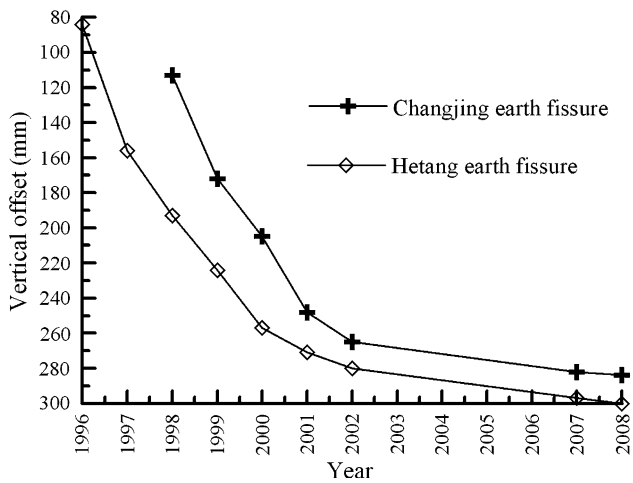


Fig. 9 Vertical offset at Changjing and Hetang Earth Fissures

In a microscope, the subsidence may demonstrate a cyclic rebound due to the seasonal fluctuation of groundwater level (Riley 1969; Xue et al. 2008; Wang et al. 2009d).

Since the total ban of groundwater withdrawal through deep wells in 2001, the groundwater level has gradually recovered and the subsidence rate has reduced to 10–20 mm/year in southern Jiangyin. Providing the prohibition remains enforced and after the secondary consolidation is complete, the land elevation may expect an uplift due to the elastic rebound of the aquifer as observed in central Taipei basin where about 10% of previous total land subsidence rebounded by 2003 (Chen et al. 2007). In the neighbouring Changzhou city, an overall elastic expansion (uplift) was observed in the unconfined aquifer (Wang et al. 2009d).

In regard to the specific geological circumstances at southern Jiangyin, two issues should be considered in the analysis and modelling. One is the creep effect of fine particle materials in the aquifer. Laboratory oedometer tests revealed a significant creep of soil samples from aquifers in Changzhou city at all stress levels from 50 to 3,200 kPa (Shi et al. 2007; Zhang et al. 2007b). Wang et al. (2009d) interpreted the creep effect on the compaction of CA1 and CA2 in Changzhou city based on the strata settlement data between 1984 and 2002 acquired through 11 borehole extensometers installed at different depths. The implication is that the creep is a significant contributor to the aquifer settlement even at an early primary pumping stage. As Changzhou is about 25 km from Jiangyin and of similar geological and hydrogeological settings, the creep effect can be expected in the aquifers in Jiangyin. The other issue is the geological and consolidation model. The bedrock basin in the south of the research area can be simulated as an asymmetrical cone (refer to Fig. 2). The slope on the SE half of the cone is much steeper than that on the NW half. The basin would have controlled the ancient

sedimentation, for example, the CA2 stratum is much thicker and deeper inside the basin but much thinner or does not exist outside. On the other hand, the wall of the basin forms a barrier that may cut off or change the horizontal groundwater flow in the vicinity during the course of intensive groundwater extraction, resulting in a sharp drawdown of groundwater inside the basin, e.g. 3.26 m/year at Hetang. Therefore, three dimensional consolidation may be more appropriate for the land subsidence and earth fissure analysis in southern Jiangyin.

Groundwater depletion can lead to earth fissures as well as land subsidence. Earth fissures under regional land subsidence are generally contributed by heterogeneities of Quaternary and anomalies of bedrock (Ayalew et al. 2004; Wang et al. 2009c). The consolidation and/or compaction of the heterogeneous Quaternary over such bedrock structures may be uneven and result in fissuring. The mechanism of earth fissuring was analogized to a rotational slab over a buried scarp or ridge due to differential subsidence in addition to other mechanisms, e.g. differential lateral movement and stretching of ground surface (Bouwer 1977). Consolidation and ground loss theories are employed to quantify the horizontal and vertical displacements of sediments over a sinusoidal basement to compute the land subsidence and the location of earth fissuring (Rojas et al. 2002). Horizontal hydraulic driving forces played a crucial role in generating fissures at depth (Helm 1994) and the governing equation was used to simulate the development of earth fissuring in a conceptual model of heterogeneous thickness of highly compressible clay (Sheng et al. 2003). Ideally, three-dimensional deformation analyses should be pursued to simulate the development of earth fissuring based on site-specific soil failure criteria. However, the application may be challenging in engineering practice due to the demand for more computer resources and more accurate soil parameters from more extensive field and laboratory investigations (Xu et al. 2008).

The development of earth fissuring in southern Jiangyin may be interpreted as a combination of multi-mechanisms. Firstly, as CA2 is thicker and deeper inside the asymmetrical basin than outside and absent above the ridge, a large differential subsidence has occurred from the ridge towards the centre of the basin (See Fig. 6). The longitudinal axis of the subsiding basin is close to Mazhen and Hetang–Wenlin ridges (Fig. 6). As the Quaternary sediments rotate inwards, a tension crack is to occur above the ridge. Secondly, the dramatic drawdown of groundwater inside the basin may cause a sharp hydraulic gradient especially in the transverse direction of the basin near the ridge where a slower drawdown is expected as CA2 is absent. This will cause a significant movement of sediments towards the longitudinal axis (or centre) of the basin as the seepage force is proportional to the hydraulic gradient. Thirdly, the

slope is much steeper along the inward shoulder of Changjing–Hetang–Wenlin ridge than that of Qiaoqi–Yunting–Huaxi ridge; there is a steep slope between 100 and 150 m below the ground surface at Changjing (Wang et al. 2009c) and a 12.5° slope at Hetang. This facilitates the geometrical conditions to develop sufficient tensile and/or shear strains to trigger earth fissuring along the inward shoulder of Changjing–Hetang–Wenlin ridge. As manifested on the ground surface, Changjing, Hetang and Wenlin earth fissures are nearly parallel to the ridge. For simplicity, the occurrence of earth fissures at Changjing, Hetang and Wenlin may be examined by plane strain analysis through a plane perpendicular to the Hetang–Wenlin bedrock ridge. As an example, the horizontal tensile strain is estimated at about 0.1% and the shear strain 0.4% at Hetang earth fissure (Wang et al. 2009a). The calculated horizontal strain is in line with the observation that the tension strain required for the development of a crack generally ranges from 0.1 to 0.4% (Jachens and Holtzer 1980).

Conclusion

The maximum accumulated land subsidence has reached 1,310 mm near the centre of the subsiding trough in southern Jiangyin due to excessive groundwater withdrawal from the second confined aquifer while there is no significant subsidence in the north and around the outcrops in the southern edge. In addition, earth fissures have occurred at Changjing, Hetang and Wenlin which forms an arc towards the subsidence trough. An ancient Yangtze River course underlies and passes through southern Jiangyin, forming a local basin surrounded by bedrock ridges or ancient river banks. The special bedrock structure would have controlled the ancient sedimentation of Quaternary which demonstrates significant heterogeneities; for example, the second confined aquifer is much thicker and deeper inside the basin than outside and absent above the ridge. The large differential land subsidence from the centre to the edge of the basin would be a direct consequence of land deformation of the heterogeneous sediments. The development of earth fissures along the Changjing–Hetang–Wenlin arc might be a combination of the inward rotation of sediments due to a large differential subsidence, the inward movement driven by a large seepage force and the steeper slope along the SE shoulder of the basin that facilitates the development of horizontal tensile strain and/or shear strain required for soil failure.

The groundwater level in the aquifer is gradually recovering, the subsidence rate is slowing down and no new earth fissure zone is occurring in southern Jiangyin as

a result of the total ban of deep groundwater extraction enacted in 2001. Even if the prohibition is not lifted, the recovery of the groundwater level in the second aquifer will be prolonged as the recharge is poor.

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