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Land subsidence and earth fissures due to groundwater withdrawal in the Southern Yangtse Delta, China

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Abstract Excessive extraction of groundwater has caused severe land subsidence and earth fissures in the Southern Yangtse Delta, China. Based on field data, the temporal and spatial distribution of land subsidence is investigated and the causes for earth fissures are analyzed. The areal distribution of the land subsidence is closely related to the cones of depression in the main exploited aquifers. The compaction of a hydrostratigraphic unit depends on its mechanical behavior, thickness, compressibility, and the piezometric level changing. The primary subsidence layers in Shanghai have been the first aquitard before 1990 and the third confined aquifer since then. But the second aquitard unit was the primary subsidence layer in Changzhou. Earth fissures, trending in several directions, occurred in the Husu tectonic zone. They were mainly caused by differential subsidence and horizontal displacement that resulted from tensile stress and shear stress in units. The majority of fissures in the study area are tensile.

Keywords Land subsidence · Earth fissure · Groundwater extraction · Aquifer system compaction · The Southern Yangtse Delta

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Introduction

The Southern Yangtse Delta is one of the most densely populated and developed areas in China. It is bounded by the East China Sea on the east and the Yangtse River on the north. It occupies an area of nearly 30,340 km^2, including SXC (Suzhou, Wuxi, and Changzhou cities) of Jiangsu Province, HJH (Hangzhou, Jiaxing, and Huzhou cities) of Zhejiang Province, and Shanghai, as illustrated in Fig. 1. The Southern Yangtse Delta has a low and flat ground surface, with a mean altitude of 3–5 m and a gentle inclination from the west to the east. The surface water in this area cannot satisfy the domestic and industrial requirements. Consequently, the groundwater has been extracted for over 100 years. Excessive groundwater withdrawal has caused severe land subsidence and earth fissures in the South Yangtse Delta. The maximum subsidence has reached approximately 3 m and 25 earth fissures have occurred by 2005. Land subsidence and earth fissures cause substantial damage, including the loss of ground surface altitude, cracking of buildings, failure of underground pipelines, and increase of flood hazards. This damage results in huge economic loss.

Land subsidence and earth fissures due to groundwater withdrawal are worldwide problems. Many areas, such as some basins in Arizona and Texas (Galloway et al. 1999), Mexico City (Adrian et al. 1999), Bangkok (Phien-wej et al. 2006), Venice (Gambolati and Freeze 1973), and Shanghai (Zhang and Wei 2005), have encountered these problems. The existing data indicate that the maximum-recorded subsidence due to groundwater overdraft has reached 8.5 m in San Joaquin Valley in California (Lofgren 1969).
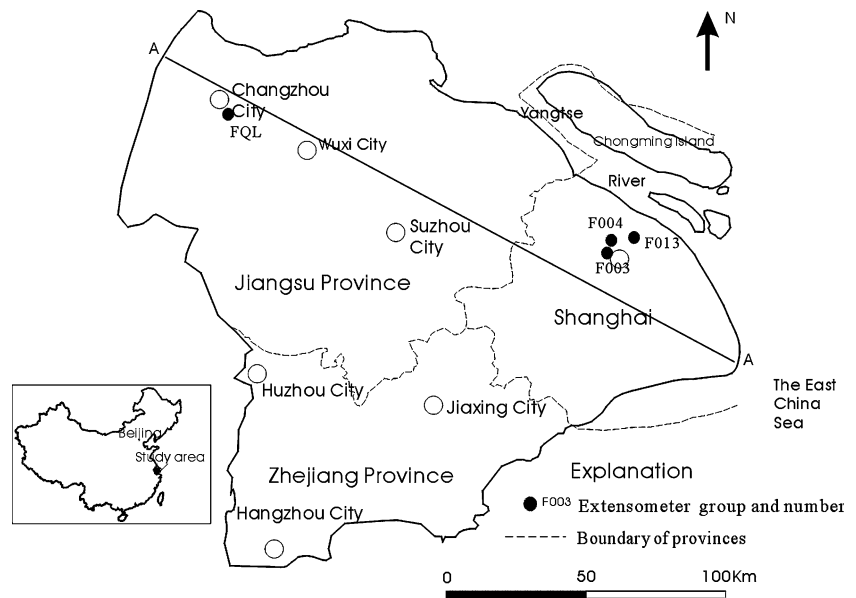
According to Terzaghi's principle of effective stresses, groundwater withdrawal from aquifer systems causes the pore water pressure to decrease and the normal effective

Fig. 1 Location of the Southern Yangtse Delta and position of extensometer groups and cross section A–A

stress to increase. The increasing normal effective stress results in compaction of hydrostratigraphic units and land subsidence. In most studies of land subsidence caused by groundwater withdrawal, only the vertical deformation was considered and the horizontal deformation was usually ignored (Adrian et al. 1999; Hanson et al. 2005). However, the drawdown of the piezometric level caused by groundwater withdrawal is actually not uniform on a horizontal plane. It usually has a cone-shaped geometry (cone of depression), with the center located in the area of pumping overdraft. Consequently, the increase in effective stress on the horizontal plane is non-uniform, causing the hydrostratigraphic units to move both vertically and horizontally. Vertical movement causes land subsidence and differential horizontal movement may result in the formation of earth fissures. Su et al. (1998) performed a field-pumping test in an unconfined aquifer and founded that the hydrostratigraphic units moved both in vertical and horizontal directions. In addition, the maximum cumulative horizontal displacement was of the same order of magnitude as the maximum cumulative vertical displacement. Wolff (1970) measured the radial strain caused by pumpage from a single well and founded that an inner zone of radial compression (positive radial strain) was surrounded by an outer zone of radial extension (negative radial strain) and that the perimeter of zero radial strain coincided with the perimeter of maximum radial displacement which was inward toward the discharge well.

Accompanying with land subsidence, earth fissures usually occur. There are two broadly accepted mechanisms for earth fissures related to groundwater withdrawal: vertical differential compaction (Bouwer 1977; Holzer and

Pampeyan 1981) and horizontal strain induced by horizontal fluid flow within the aquifer system (Helm 1994). Bouwer (1977) assumed that the hydrostratigraphic units moved only in vertical direction and calculated land subsidence at different sites by elastic or logarithmic theory due to change in pore water pressure. He then explained the formation of earth fissures above 'scarps' and ridges in the bedrock on the basis of the rotating-slab theory. Holzer and Pampeyan (1981) investigated four linear earth fissures in Arizona, California, and Nevada. The surveys indicated that the four fissures were coincident with zones of localized differential subsidence and occurred near points of maximum convex-upward curvature in subsidence profiles. Helm (1994) proposed a Darcy–Gersevanov expression for the velocity of solids that constituted an aquifer matrix and explained the occurrence of vertical fissures in distant areas where drawdown, subsidence and surface bending were negligibly small to nonexistent.

The occurrence and magnitude of land subsidence and earth fissures are related to the geological structure, mechanical behavior of hydrostratigraphic units, and extraction of groundwater. Land subsidence and earth fissures occur and develop in a different way in each area. In some areas such as Shanghai, only land subsidence has occurred. In other areas such as SXC, both land subsidence and earth fissures were observed. This paper aims at discussing the characteristics of land subsidence and earth fissures in the Southern Yangtse Delta on the basis of field data of piezometric level and compaction of hydrostratigraphic units. These aspects are useful for groundwater management, engineering construction, and preventive planning.

Geological background

Sedimentary and igneous rocks constitute the basement of the Southern Yangtse Delta. The primary faults, which only affect bedrock, mainly trend NE-SW and NW-SE, as shown in Fig. 2. Husu Fault divides the study area into the Suxi and the Kunhuhang tectonic zones, which are in the north-western and southeastern parts with respect to the fault, respectively. In the Suxi tectonic zone, anticlines and synclines extending mainly NE-SW form ridges and valleys in the bedrock. In the Kunhuhang zone, the domes of Jurassic and Cretaceous igneous rocks scatter intermittently along NE-SW. Figure 3 indicates the isopach map of unconsolidated sediments. The data source is from the Information Center of Jiangsu Institute of Geological Survey. The thickness of the Quaternary deposits which is influenced by the basal structures and paleotopography increases from the western part to the eastern part of the Southern Yangtse Delta. It is thinner than 100 m in Huzhou City and greater than 360 m in Congming Island, north of Shanghai.

The Quaternary deposits are alluvial, lacustrine, marine, and palustrine, including clay, silty clay, silt, sand, and gravel. The Quaternary deposits can be considered to be composed of five aquifers: an unconfined aquifer and four confined aquifers denoted from top to bottom as A1–A4 in Fig. 4, respectively. The aquifers are composed primarily of sand and gravel. The confining aquitards interbedded between aquifers are called aquitards 1–5 from top to bottom and are composed of clay and silty clay. Except for the fourth confined aquifer, which is primarily restricted to the northern part of Shanghai and the northeastern part of Suzhou, other aquifers are continuous across the entire study area. The first aquitard unit, which occurs mainly beneath Shanghai and Suzhou cities, is composed primarily of soft clay. The other four-aquitard units consist primarily of stiff to hard clay and silty clay. The demands for groundwater exploitation and the conditions of aquifers change in different cities. Therefore, the mainly exploited aquifer units and the magnitude of groundwater pumpage vary from city to city.

Change in piezometric level and aquifer system deformation

Extraction of groundwater and resultant change in piezometric level

Variations in pumpage of groundwater and the exploited aquifers result in different evolutionary histories of piezometric level. Figure 5 shows the amount of net groundwater pumpage from individual confined aquifers in Shanghai from 1961 to 2000. Figure 6 indicates representative changes in piezometric level in Shanghai and Changzhou.

Extraction of groundwater in Shanghai began in 1860 and extensive exploitation occurred in the 1950s when 80.5% of the total pumped water was obtained from the first and the second confined aquifers. Consequently, land surface subsided rapidly in the period 1957–1960, with an average rate of 110 mm/a. The piezometric level in those two aquifers declined to the historical lowest values in the early 1960s. The lowest piezometric level was lower than –30 m. In order to prevent the piezometric level from declining continuously, the amount of groundwater pumpage was decreased significantly and artificial recharge was

Fig. 2 Tectonic map of bedrock in the Southern Yangtse Delta (modified after NIGMR et al. 2003)
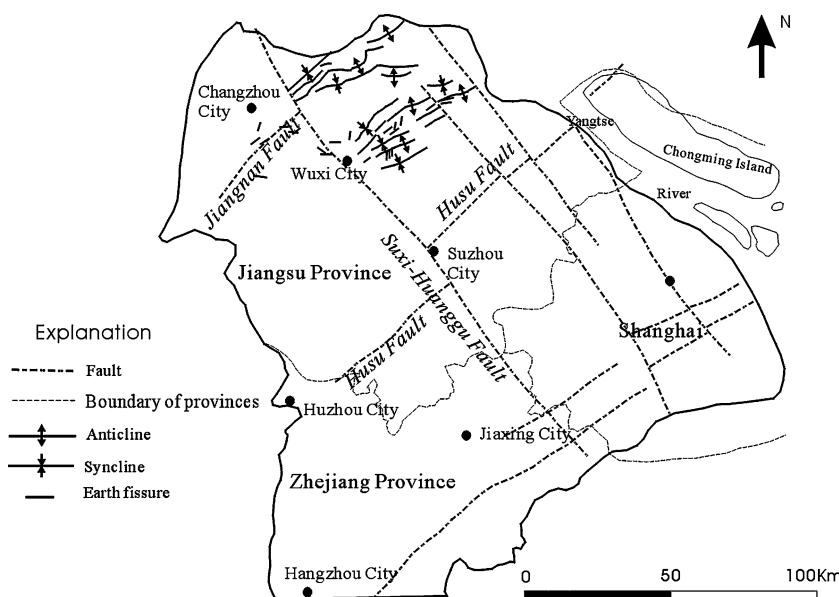
Fig. 3 Isopach map of unconsolidated sediments in the Southern Yangtse Delta (modified after NIGMR et al. 2003) (**a**). Enlarged map of the selected area by a *rectangle* (**b**)
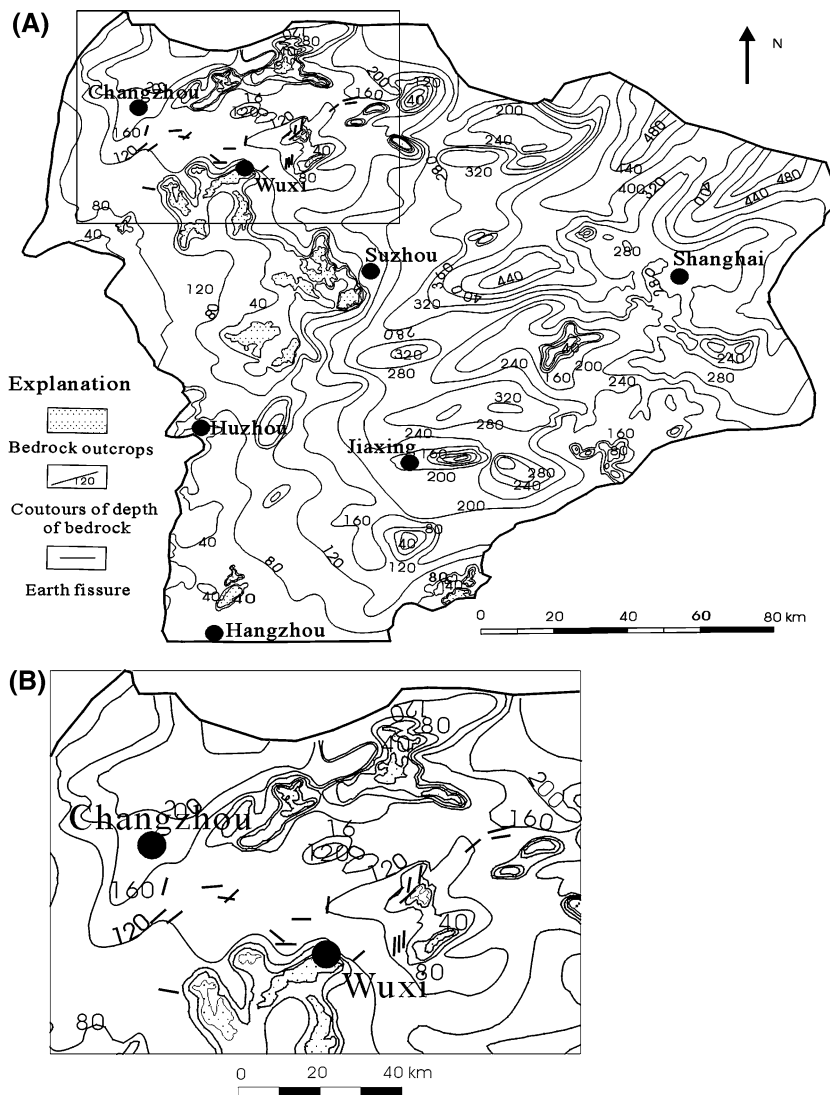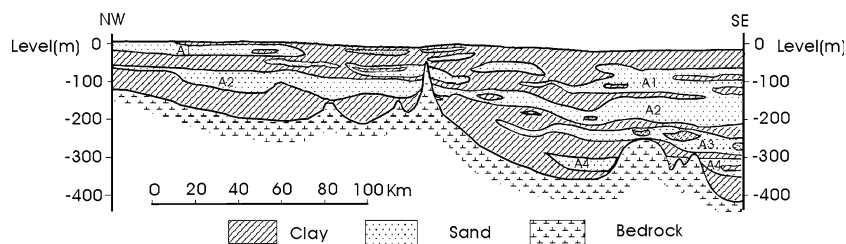
Fig. 4 Conceptual hydrogeological cross section of the Southern Yangtse Delta (A–A in Fig. 1)

carried out after 1966. The main exploited aquifers also changed gradually to the third and fourth confined aquifers, thus piezometric level in the first and the second confined aquifers rose rapidly to higher than –5 m by the early 1970s and then fluctuated within a certain range with the average remaining nearly constant. The rate of land subsidence correspondingly decreased and even some recovery occurred over the period 1966–1971. The demand for groundwater increased again in the late 1980s, especially after 1990 in Shanghai city. In order to prevent rapidly

increasing land subsidence as occurred in the late 1950s and the early 1960s, most groundwater was pumped from the third and the fourth confined aquifers. The groundwater from these two aquifers accounted for 70 and 15% in 2000, respectively (Wei 2002). This caused the piezometric level in the third confined aquifer to decline continuously till 1998 when pumpage decreased substantially. Then, the piezometric level in the third confined aquifer remained nearly constant and even a little rise occurred. The piezometric level in the fourth confined aquifer changed in a
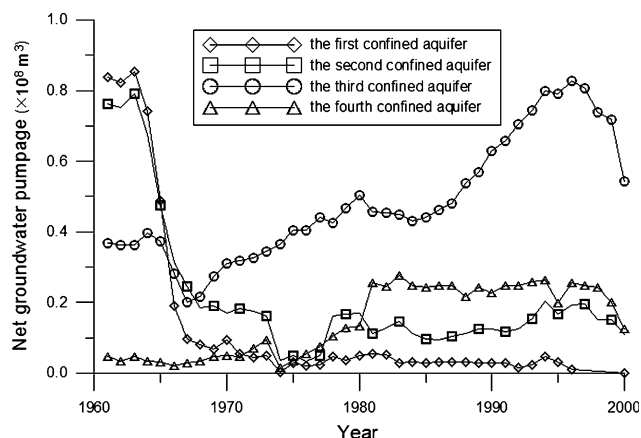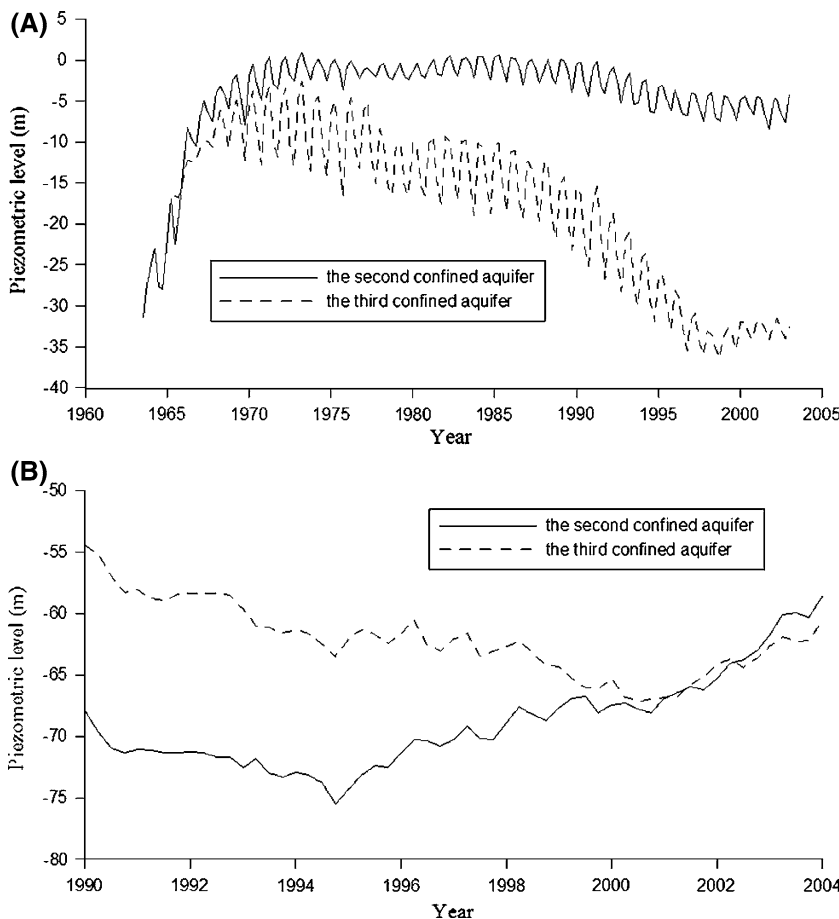
Fig. 5 Amount of net groundwater pumpage from individual confined aquifers in Shanghai from 1961 to 2000

similar pattern to that in the third confined aquifer. The piezometric level in the first and the second confined aquifers also declined in the late 1980s as a consequence of the increasing pumpage and the rapid decrease of piezometric level in the underlying third confined aquifer. However, they were much higher than the previous lowest values that occurred in the 1960s.

Groundwater extraction dates back to 1927 in the SXC area and extensive exploitation occurred after 1983 when the town industries developed rapidly. Groundwater was mainly pumped from the first and the second confined aquifers. The piezometric level in aquifer systems decreased continuously before 1995. Then, the strict restrictions led to a substantial pumpage reduction, causing the piezometric level to rise gradually. The People's Congress of Jiangsu Province issued a resolution in 2000 to prohibit extracting groundwater in SXC, and the piezometric level consequently rose rapidly afterwards. The second confined aquifer was the main productive aquifer. Pumpage from this aquifer increased gradually year after year from 4×10^7 m^3/a in the 1960s to 1×10^8 m^3/a in the early 1980s, and remained within the range of 7.5×10^7–9×10^7 m^3/a afterwards. The depth of the piezometric level at the center of the cone of depression of the second confined aquifer in Changzhou decreased from 20 m in the 1960s to 82.3 m in 1994 (Wu 1999). Then, the piezometric level rose gradually as a consequence of a significant decrease in groundwater abstraction. The piezometric level at extensometer group FQL rose from the previous lowest value −75.53 m in 1994 to −58.63 m in 2003. Due to flow from the third confined aquifer to the second confined

Fig. 6 Piezometric level changes in individual aquifers in Shanghai (**a**) and Changzhou (**b**)

aquifer induced by pumpage in the latter, the third confined aquifer experienced a similar changing pattern of piezometric level to the second confined aquifer though it was not largely pumped in SXC. The center of the cone of depression was located north of Changzhou, with the piezometric level approximately at –60.0 m in 2003.

Groundwater extraction began in 1914 in HJH and the second and the third confined aquifers were the main exploited hydrostratigraphic units. Extensive abstraction of groundwater occurred after 1980, increasing from $5.58 \times 10^7 \, m^3$ in 1980 to $1.21 \times 10^8 \, m^3$ in 1990. Then the rapid increasing trend of pumpage stopped and remained nearly constant (Zhao et al. 2006).

Compaction of hydrostratigraphic units

In the study of land subsidence and accompanying earth fissures due to groundwater withdrawal, the aquifer units were often treated as linear elastic materials, and the aquitard units were often treated as bi-linear materials (Bouwer 1977; Pacheco et al. 2006). However, monitoring field data of compaction and piezometric level records from the extensometer groups and observation wells in the Southern Yangtse Delta indicate that deformation of hydrostratigraphic units is complex being largely related both to the properties of soils and the piezometric level changing patterns (Zhang et al. 2007).

Different hydrostratigraphic units may have different deformational behaviors under the same changing patterns of piezometric level. When the piezometric level rose continuously and remained nearly constant afterwards, the aquifers consisting primarily of sands and the aquitards made up chiefly of stiff clays mainly exhibited elastic behavior. They underwent contraction and expansion alternatively closely following the dropping and rising cycles of piezometric level. Figure 7 shows the cumulative compaction curve of the third confined aquifer versus the piezometric level in this aquifer unit at extensometer group F003 in Shanghai (positive values indicate compaction and negative values indicate expansion in this paper). As can be seen in Fig. 7, the piezometric level nearly fluctuated within a certain range before 1989 and the third confined aquifer exhibited elastic behavior. However, under a similar changing pattern of piezometric level, the aquitards consisting primarily of soft clays presented continuous compaction, exhibiting visco-elasto-plastic behavior. Figure 8 shows the relationship between the compaction of the first aquitard with the piezometric level in the first confined aquifer at extensometer group F013. When the piezometric level remained nearly constant or changed a small amount, the first aquitard compacted continuously and no expansion occurred in the yearly rise of piezometric level.
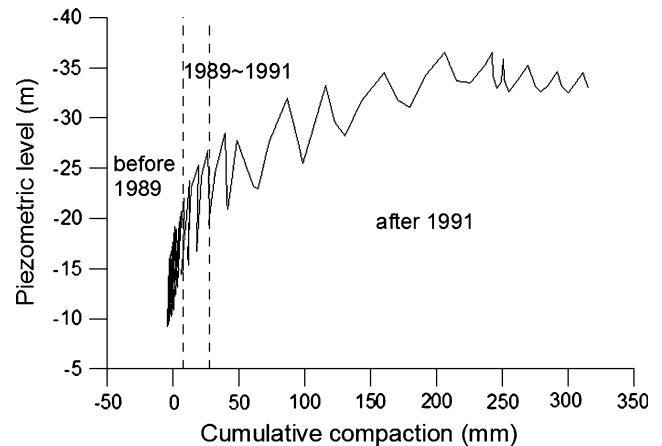

Fig. 7 Curve of cumulative compaction versus piezometric level in the third confined aquifer at extensometer group F003
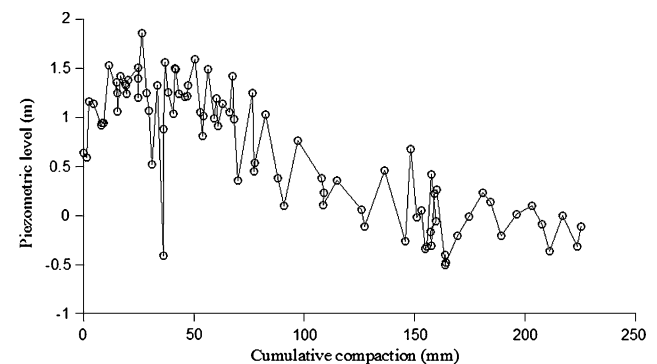

Fig. 8 Curve of cumulative compaction of the first aquitard and piezometric level in the first confined aquifer at extensometer group F013

Like the aquitards consisting of soft clay, the aquifers consisting of sands may exhibit visco-elasto-plastic behavior under certain changing patterns of piezometric level, and the compaction lags behind the change in piezometric level. A significant part of the monitoring data indicates that the mechanical behavior of aquifers is closely related to the changing patterns of their piezometric level. When the piezometric level decreased but was above its previous lowest level, the aquifer compacted and expanded closely following the declining and rising piezometric level, and obviously there was irrecoverable plastic compaction in each yearly cycle. The aquifer exhibited elasto-plastic behavior, as shown by the curve within 1989–1991 in Fig. 7. When the piezometric level decreased below its previous lowest value the aquifer had experienced, it did not expand but compacted continuously in yearly rises. The compaction of aquifers lagged behind the change in piezometric level. The aquifer exhibited visco-elasto-plastic mechanical behavior, as shown by the curve after 1991 in Fig. 7.

A hydrostratigraphic unit may exhibit different mechanical behaviors because of different changing patterns of piezometric level. As shown in Fig. 7, the third confined aquifer in Shanghai exhibit different mechanical behaviors in different periods. A hydrostratigraphic unit may also exhibit different mechanical behaviors at different sites, such as at the center or the edge of the cone of depression, within the same period. Figure 9 shows the compaction curves of the second confined aquifer versus the piezometric level changes in the second confined aquifer. Extensometer group F004 in Shanghai is located in the edge of the cone of depression of the second confined aquifer (Fig. 10). The aquifer at extensometer group F004 compacted and expanded closely following the piezometric level declining and rising cycles, but there was obvious irrecoverable compaction in each yearly cycle, as shown in Fig. 9a. The aquifer exhibited primarily elasto-plastic behavior during the period 1989–2002. Conversely, extensometer group FQL in Changzhou is located in the center of the cone of depression (Fig. 10). The aquifer unit at this site exhibited continuous compaction even though the piezometric level rose continuously after 1994 (Fig. 9b). This compaction trend did not stop until 2001. Then the curve
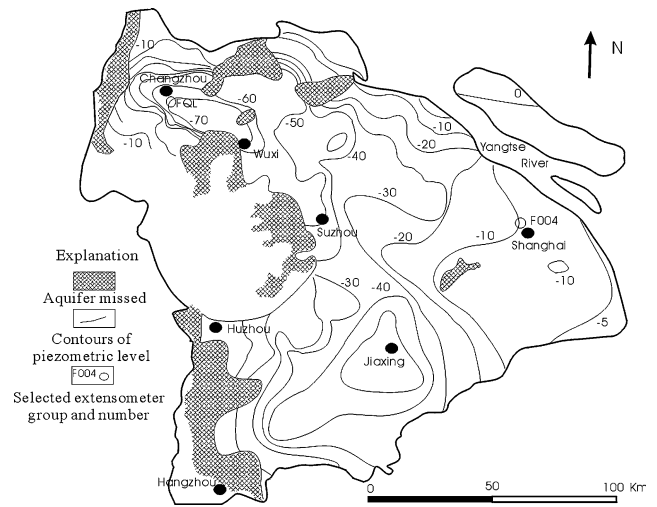

Fig. 10 Contours of groundwater level in the second confined aquifer in 2002 (according to Zhang and Wei 2005)

was essentially vertical, indicating that the elastic expansion caused by the rising piezometric level was nearly counterbalanced by the continuing compaction. After 2002, the curve moved to the left, indicating that the elastic

Fig. 9 Curve of cumulative compaction and piezometric level changes in the second confined aquifer. **a** Over the period 1989–2002 at extensometer group F004 in Shanghai. **b** Over the period 1990–2003 at extensometer group FQL in Changzhou

expansion exceeded the continuing compaction and net expansion occurred. The compaction of the second confined aquifer lagged behind the change in piezometric level at extensometer group FQL and exhibited visco-elato-plastic behavior during the period 1990–2003.

## Features of land subsidence in the Southern Yangtse Delta

Land subsidence in the Southern Yangtse Delta was first reported in 1921 in Shanghai and was then documented successively in HJH and SXC in the 1960s. Land subsidence has close temporal and spatial relations to the groundwater pumpage. The rate of land subsidence increased significantly over the large exploitation period. In the period when pumpage decreased greatly and piezometric level remained constant or rose, the rate of subsidence decreased significantly and even some recovery occurred. As a consequence of temporal and spatial variations in groundwater pumpage, land subsidence has evolved in a different way from city to city and from time to time in the study area.

Land subsidence in Shanghai can be separated into seven stages: increasing (1921–1948), strongly increasing (1949–1956), very strongly increasing (1957–1961), decreasing (1962–1965), rebounding (1966–1971), slightly increasing (1972–1989), and slowly increasing (1990–2001). The mean rates of subsidence in those seven stages were 24, 40, 110, 60, –3, 3.5, and 16 mm/a, respectively (SGEAEB 2002; Chai et al. 2004). Land subsidence in HJH began in 1964 and can be separated into four stages: increasing (1964–1973), strongly increasing (1974–1983), very strongly increasing (1984–1990), and slowly increasing (1991–2005). The corresponding rates of land subsidence at the downtown of Jiaxing City in those four stages were 7.9, 29.6, 41.9, and 19.0 mm/a, respectively. After 1991, the center of subsidence moved gradually from downtown of Jiaxing City to Haiyan County, nearly 35 km southeast of the former (Fig. 11). Cumulative land subsidence in 2005 was 1,097 mm in Haiyan and 882.5 mm in downtown of Jiaxing City (Zhao et al. 2006). In the SXC area, land subsidence was increasing in the period 1960–1985, and very strongly increasing in the period 1986–1995, when the subsidence rate reached 109 mm/a. The land subsidence rate has slowed down since 1995 because the groundwater pumpage was strictly limited. Though the rate of subsidence has decreased in the entire southern delta in recent years, the area affected by land subsidence is still expanding.

In the early period of groundwater pumpage, the cones of depression occurred separately in the overdraft areas and the corresponding areas of land subsidence were not connected. Owing to the rapid economic development after the 1980s, the requirements for groundwater increased significantly, and the number of wells increased largely. The wells were located not only in cities but also in the counties and towns around the cities. The cones of depression coalesced forming a regional cone of depression. The areas influenced by land subsidence expanded and the early isolated subsidence bowls connected. By the late 1990s, the entire Southern Yangtse Delta had been affected by land subsidence. In 1999 the area where cumulative subsidence had exceeded 200 mm covered nearly 10,000 km^2; one third of the whole study area (Fig. 11). The comparison of Figs. 10 and 11 reveals that the centers of land subsidence are nearly coincident with the cones of depression in the second confined aquifer in SXC and HJH. However, this is not the case in Shanghai. The reason for this is that the second confined aquifer was the main exploited aquifer in SXC and HJH and land subsidence there was closely related to the decreasing piezometric level in the second

Fig. 11 Contours of cumulative land subsidence from 1956 to 1999 and distribution of earth fissures (modified after Zhang and Wei 2005)
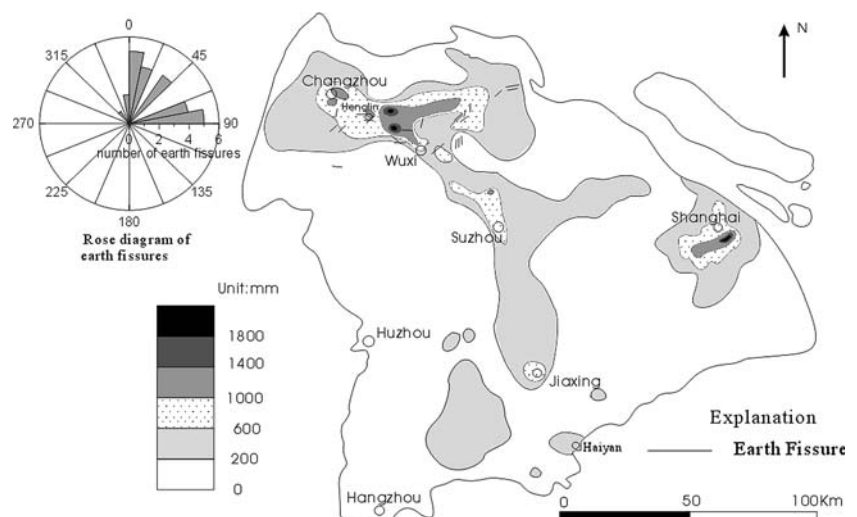
confined aquifer. Land subsidence in Shanghai, however, was primarily related to the decreasing piezometric level in the second and the third confined aquifers. Besides the changing piezometric level in aquifers, land subsidence is also related to the texture and compressibility of soils that constitute the hydrostratigraphic units, the thickness of units, and the changing patterns of piezometric level the units have experienced. All these factors influence the land subsidence and explain why the subsidence bowls are not exactly consistent with the cones of depression.

Those mentioned factors also influence the contribution of individual units to the total subsidence. Table 1 indicates the percentage contribution of individual units to the total subsidence at extensometer groups. In the period 1981–1990, piezometric level in all aquifers in Shanghai decreased slightly and land subsidence increased slowly. The first aquitard overlying the first confined aquifer is composed of highly compressible muck and mucky clay, which have higher moisture content than their liquid limit and have a void ratio of greater than 1.5 for the former and 1.0–1.5 for the latter. The compaction of the first aquitard continued even though the piezometric level remained nearly constant or changed scantly. On the other hand, the hydrostratigraphic units underlying the first confined aquifer have medium to low compressibility and their compaction was small when the piezometric level changed a small amount. Therefore, compaction of the first aquitard unit contributed much to the total subsidence and became the primary subsidence layer during the period 1981–1990. In the period 1991–2000, piezometric level in all aquifers declined more rapidly than before and the rate of land subsidence increased rapidly too. In the first and the second confined aquifers in Shanghai, the changes in piezometric level were small and higher than their previous lowest values, whereas piezometric level in the third confined aquifer decreased rapidly after 1990 and was below the previous lowest value. Furthermore, the third

confined aquifer has large thickness. Therefore, the compaction of the third confined aquifer in Shanghai was visco-elasto-plastic and increased more rapidly than that of other units, even though the compaction of all units increased in the period 1991–2000. The third confined aquifer contributed more than 60% to the total subsidence and was the main subsidence layer in Shanghai in the period 1991–2000. The data from extensometer group FQL in Changzhou indicate that the compaction of the second aquitard unit accounted for more than 50% of the total subsidence and the second aquitard unit was the main subsidence layer in this area. The reason for this is that the second confined aquifer underlying the second aquitard was the main exploited aquifer in Changzhou and the second aquitard is approximately 74 m in thickness, in which a subunit of mucky clay (about 20 m in thickness) is present.

As discussed above, whether or not a hydrostratigraphic unit is a main subsidence layer depends on many factors, such as the main exploited aquifer, the compressibitlity of soils making up the hydrostratigraphic unit, the thickness of the unit, and the changing patterns of piezometric level the unit has experienced. Thus the main subsidence layer changes through time and space. In some appropriate conditions, an aquifer unit may be the main subsidence layer.

Earth fissures

Characteristics of the earth fissures

The first earth fissure in the Southern Yangtse Delta occurred in 1989 in Henglin Town, 18 km southeast of Changzhou City (Fig. 11). Since then, 25 earth fissures have been documented. Most of those earth fissures extend through densely populated towns. They have caused

Table 1 Percentage of contribution of individual hydrostratigraphic units to the total subsidence at extensometer groups

Unit	F003		F004		FQL
	1981–1990	1991–2000	1981–1990	1991–2000	1984–2003
Top soil	34.5	2.9	7.5	5.4	–0.3
Unconfined aquifer					
The first aquitard	54.3	11.3	43.4	19.4	Missed
The first confined aquifer	7.9	6.5	25.7	15.6	1.4
The second aquitard					56.3
The second confined aquifer					10.9
The third aquitard	4.4	10.9	4.9	9.2	6.8
The third confined aquifer	18.6	62.1	12.0	64.5	20.0
The fourth aquitard	–19.7	6.3	6.5	–14.3	4.9
The fourth confined aquifer					
The fifth aquitard					

damage to approximately 1,400 houses and resulted in more than 0.5 billion economic loss. Earth fissures have occurred primarily in the Suxi tectonic zone, northwest of Husu Fault, where groundwater was extensively extracted and land subsidence was severe (Fig. 11). The majority of fissures are tensile and some are shearing in form. On the ground surface, localized differential subsidence or horizontal tension on both sides of earth fissures can be observed (Fig. 12). Earth fissures often occur in belts. An earth fissure belt is composed of a main fissure and several subordinate fissures which distribute on both sides of the main fissure. A fissure belt is often 30–100 m in width and 200–2,000 m in length (Wu et al. 2003). The maximum differential subsidence on both sides of earth fissures is 20 cm, and the width of a single fissure is 3–6 cm. Earth fissures trend in many directions, as shown by the rose diagram inset in Fig. 11.

Earth fissures occurred extensively in the 1990s and about 80% fissures occurred in the period 1990–1996 when intense groundwater abstraction was carried out in this area. The development of earth fissures slowed down after 2000. The occurrence of earth fissures in the Southern Yangtse Delta is temporally and spatially related to the extraction of groundwater. The Seismological Bureau of Jiangsu Province used several methods to detect faults in the Quaternary deposits, including shallow artificial earthquakes, accurate magnetic surveying, shallow drilling, and seismic profiles. It was found that there were no the Quaternary faults and the Holocene faults in the area where earth fissures occurred extensively (Gao et al. 1997). Therefore, the occurrence of earth fissures in the Southern Yangtse Delta is related to groundwater withdrawal rather than neotectonic activity.

Fig. 12 An earth fissure induced by groundwater withdrawal

Mechanics of earth fissures

Extraction of groundwater causes the pore water pressure to decrease and the effective stress to increase both in vertical and in horizontal directions. Where the drawdown of piezometric level is greater, the change in effective stress is greater. Change in effective stress is non-uniform in hydrostratigraphic units, causing the strain and displacement in vertical and horizontal directions to vary from site to site. For simplicity, a bidimensional strain problem is taken as an example. Considering an infinitesimal rectangular element at a point in the units with sides parallel to axes x and z, the stress components (σ_x, σ_z, τ_{xz}) acting on sides are shown in positive senses in Fig. 13. The principal stresses at this point can be calculated by Eq. 1

$$\frac{\sigma_1}{\sigma_3} = \frac{\sigma_x + \sigma_z}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_z}{2}\right)^2 + \tau_{xz}^2} \qquad (1)$$

where σ_1 is maximum principal stress, σ_3 is minimum principal stress (positive values indicate compressive stress and negative values indicate tensile stress). The angle between minimum principal stress and the positive direction of x axis is denoted by α and can be calculated by Eq. 2

$$tg\alpha = \frac{\tau_{xz}}{\sigma_3 - \sigma_z} \qquad (2)$$

When σ_3 is smaller than the tensile strength of soils, cracking, which is perpendicular to the minimum principal stress, occurs and the fissure is tensile. According to the Mohr–Coulomb failure criterion, the shear failure will occur and shear fissures are observed if the principal stresses σ_1 and σ_3 satisfy Eq. 3

$$\sin\varphi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2c \cdot ctg\varphi} \qquad (3)$$

where φ is the internal friction angle and c is cohesion of soils. Before the failure occurs, the strain and displacement are related by Eq. 4

$$\begin{cases} \varepsilon_x = \dfrac{\partial u}{\partial x} \\[2mm] \varepsilon_z = \dfrac{\partial v}{\partial z} \\[2mm] \gamma_{xz} = \dfrac{\partial v}{\partial x} + \dfrac{\partial u}{\partial z} \end{cases} \qquad (4)$$

where u is horizontal displacement; v is vertical displacement; ε_x is horizontal strain resulting from non-uniform horizontal displacement; ε_z is vertical strain which is usually compressive; γ_{xz} is shear strain, with the first term
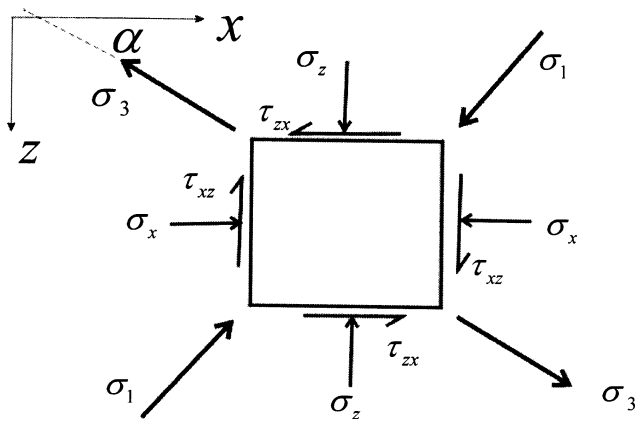
Fig. 13 Infinitesimal element and stress components

$(\partial v/\partial x)$ indicating the differential vertical displacement on the same horizontal plane and the second term $(\partial u/\partial z)$ indicating the differential horizontal displacement on the same vertical plane. When the stress components σ_x and σ_z remain constant, σ_3 may be tensile if τ_{xz} increases. When τ_{xz} is negligible and σ_x is tensile, σ_3 is about equal to σ_x and parallel to x axis. The occurrence of earth fissures depends upon two elements: the stresses in soils and the strengths of soils making up hydrostratigraphic units. Tensile fissures are related to tensile stresses and tensile strengths, and shear fissures are related to shear stresses and shear strengths. Tensile strength is often much smaller than shear strength for soils, thus most of the observed earth fissures are tensile.

Factors influencing the tensile strength of soils include soil types, moisture content, and links between grains. Bishop and Garga (1969) performed drained triaxial tests to study the tensile failure of London clay. They found that the tensile failure was brittle and the failure strain was very small. Tensile tests on four compacted soil samples were performed in Tsinghua University (Huang 1983). It was documented that the failure strain was 0.108–0.148% and the tensile strain increased with the increasing moisture content. In the areas where differential vertical displacement and/or horizontal displacement occur largely, the strain and the stress are great. Differences in geometry, texture and compressibility of hydrostratigraphic units and in changing patterns of piezometric level can cause differential subsidence and horizontal displacement. Earth fissures, therefore, often occur associated to bedrock ridges and scarps, and the edges of subsidence bowls.

In the Suxi tectonic zone, the bedrock tectonics is complex, including several folds and faults, and some buried scarps. Locally the thickness of the Quaternary deposits changes abruptly. Additionally, pumpage of groundwater and hydraulic gradient in the second confined aquifer in the Suxi tectonic zone was great. Differential subsidence and horizontal strain were induced by those factors obviously. Hence, many earth fissures with no preferred orientation occurred. In Shanghai and Suzhou, the depth of bedrock is greater and the basement changes smoothly. The first aquitard consisting of muck and mucky clay is continuous there. Therefore, the differential subsidence was small and no earth fissures have occurred though the total subsidence was greater in this area. In the HJH area, the basement changes smoothly and no earth fissures have been observed yet. However, if groundwater is extracted continuously and land subsidence increases, earth fissures may occur because of the low depth to the bedrock.

Conclusions

Excessive extraction of groundwater has caused severe land subsidence accompanied with earth fissures in the Southern Yangtse Delta. Based on the analysis of the measured data and field investigation, the following conclusions can be drawn:

(1) The areal distribution of land subsidence is closely related to that of the cones of depression in the main exploited aquifers. The primary subsidence layer is related to the main exploited aquifer, and the thickness and the compressibility of units. Both aquitards and aquifers may become primary subsidence layers. The main subsidence layer in Shanghai was the first aquitard before 1990 and the third aquifer after 1990. The main subsidence layer in Changzhou was the second aquitard.

(2) Deformation characteristics of aquifer systems due to groundwater withdrawal are complex and are related to the changing patterns of piezometric level that the hydrostratigraphic units have experienced. Aquitard units consisting of soft clays exhibit visco-elasto-plastic behavior. Aquifers consisting primarily of sands may also exhibit visco-elasto-plastic behavior under certain conditions.

(3) Earth fissures are primarily caused by groundwater pumpage. They mainly occurred in the Husu tectonic zone where the depth of bedrock is small and the basement topography changes greatly. Influenced by many factors, such as the differences in the geometry, texture and compressibility of the hydrostratigraphic units and in the changing patterns of piezometric level the units have experirnced, the earth fissures in the Southern Yangtse Delta trend in several directions, without preferred orientation.

(4) In order to control land subsidence and earth fissures, the pumpage of groundwater has to be limited to prevent the piezometric level from declining continuously, especially from dropping below the previous lowest values the hydrostratigraphic units have experienced. Additionally, the main extracted aquifer should be as far as possible away from the soft clay units.

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