

# Investigation into subsidence hazards due to groundwater pumping from Aquifer II in Changzhou, China

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**Abstract** This paper presents an investigation into increased deformation of Aquifer II caused by groundwater pumping from the aquifer in Changzhou, China. As groundwater levels of aquifers have been decreasing in recent decades due to uncontrolled water pumping, land subsidence is becoming a serious geohazard in Changzhou. Based on recently reported field data, the compression of aquitards has not increased compared to that of aquifers with the same scale of layer thickness. The Cosserat continuum model was adopted to analyse the observed phenomenon in this study. A classic Cauchy continuum model is also used for comparison. The comparison between these two models indicates that the proposed approach can interpret the increased deformation well, and the classic Cauchy continuum model underestimates the aquifer deformation as it does not consider shear displacement and macro-rotation. A discussion on the relationship between the groundwater level in the aquifer and subsidence is then undertaken. The results show that the severity of the annual subsidence is correlated with the variation in groundwater level

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in Aquifer II. To mitigate the subsidence hazards, countermeasures should be adopted to avoid the shear stress in aquifers which results from the high hydraulic gradient, by the appropriate allocation of pumping wells and by restricting groundwater withdrawal volume from each pumping operation.

**Keywords** Groundwater withdrawal · Land subsidence · Deformation of aquifer · Cosserat continuum model

## 1 Introduction

Land subsidence has been reported in many cities in the coastal areas of China, such as the Shanghai, Tianjin, Taiyuan, and Su–Xi–Chang regions (Chai et al. 2004; Shi et al. 2007; Wang et al. 2010; Xu et al. 2008; Zhang et al. 2007). Recent research shows that groundwater withdrawal is still a primary reason for land subsidence in the coastal urban regions (Shen and Xu 2011; Xu et al. 2012a, b). According to classical soil mechanics, as the compressibility of clayey soil in an overburden aquitard due to groundwater withdrawal is much greater than that of sandy soil in the lower aquifer, it is generally considered that consolidation of aquitards due to groundwater withdrawal is the main reason for land subsidence, and therefore, the compression of aquifers can be ignored (Teatini et al. 2005; Shen et al. 2006; Xu et al. 2008; Gambolati and Freeze 1973).

The Su–Xi–Chang area (encompassing Suzhou, Wuxi, and Changzhou in Jiangsu Province), which is located to the south of the Yangtze River, is a typical area in China with serious land subsidence due to excessive groundwater withdrawal (Zhang et al. 2010). Changzhou City in the Su–Xi–Chang area experienced a maximum land subsidence rate of 147 mm/year in the early 1980s due to excessive groundwater withdrawal (Wang et al. 2009). The groundwater basin of Changzhou is a typical multi-aquifer–aquitard system (MAAS) with a phreatic aquifer, and three confined aquifers (AqI–III) (Shi et al. 2007; Wang et al. 2009). A large compression was found in the sandy aquifers of Changzhou recently (Shi et al. 2007; Wang et al. 2010). The percentage of compression deformation of AqII from 1984 to 2001 reached 12.45 % (Shi et al. 2007). This phenomenon indicates the compression deformation of the sandy aquifer cannot be ignored, although the aquitard overlying AqII was still the major compressive stratum in Changzhou City. The prediction of land subsidence in Changzhou City should therefore consider the deformation of aquitards and aquifers simultaneously.

Recently, there has been a new phenomenon in Shanghai and in the region of the Yangtze River Delta, where land subsidence and the deformation of aquifers continue to increase. At the same time, a large number of structures, such as underground rail tunnels, deep excavations, and high-rise buildings, have been constructed (Tang et al. 2008; Xu et al. 2012a; Tan and Wang 2013a, b). Some researchers have indicated that urban construction is one of the causes of the accelerated land subsidence (Tang et al. 2008; Ma et al. 2014; Wu et al. 2014; Xu et al. 2012a, 2013, 2014). However, urban construction cannot fully explain the large deformation of deeper aquifers. Since the classic Cauchy theory cannot explain the mechanics of deformation of sandy aquifers, the theory of Cosserat continuum mechanics (Cosserat and Cosserat 1909) provides a possible tool to solve the above problem. Budhu and Adiyaman (2010) proposed land subsidence mechanics based

on Cosserat continuum mechanics to predict deformation of a sand layer due to groundwater withdrawal. Budhu and Adiyaman (2010) established a two-dimensional Cosserat continuum model to predict land subsidence in Arizona, in the USA. Shen et al. (2013) used a Cosserat model to predict the deformation of confined aquifers in Shanghai. These analysis results indicate that the Cosserat model can be used to evaluate land subsidence due to groundwater withdrawal more accurately than the classic Cauchy model, because the Cosserat theory considers the shear stress in aquifers due to differences in groundwater level.

The objectives of this study are (1) to establish a modified Cosserat model for a confined aquifer in Changzhou; (2) to predict land subsidence caused by groundwater pumping in Changzhou by considering the deformation of aquitards and aquifers simultaneously; and (3) to interpret the mechanism of the strong correlation between land subsidence and groundwater level in Aquifer II in Changzhou using the proposed solution.

## 2 Background

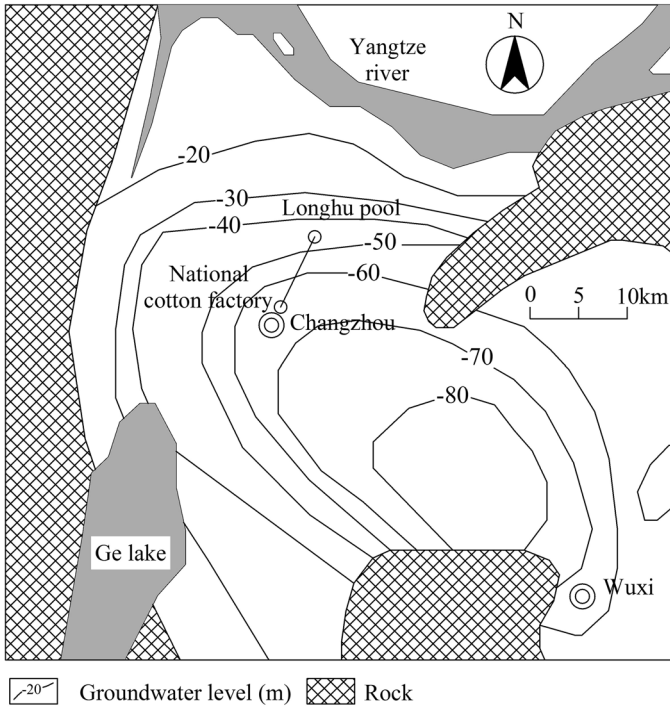
### 2.1 Geotechnical profile and soil properties

Changzhou is located on the deltaic deposits of the Yangtze River on the east coast of China. The ground elevation is between 3.8 and 7.0 m, and the thickness of the Quaternary sediments is 120–240 m, except for the outcrops to the east of Changzhou City (Wang et al. 2009). Figure 1 shows the location of the analysed area, which extends from the National Cotton Factory to Longhu Pool, and is located on the south bank of the Yangtze River and to the north of Changzhou. In this location, groundwater has been pumped continuously for domestic and industrial use in recent decades.

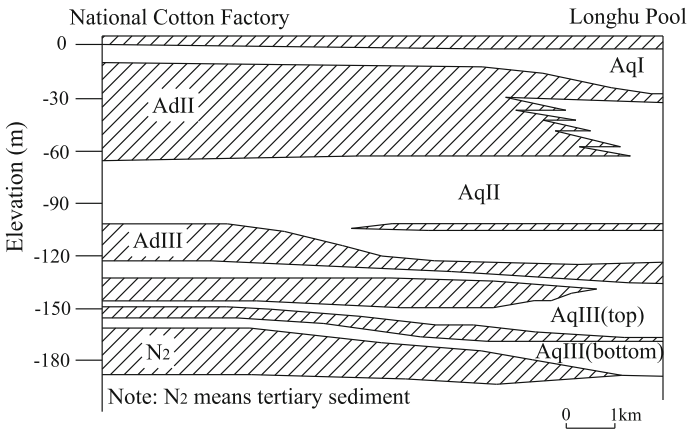
The groundwater basin is composed of a phreatic aquifer, three confined aquifers (labelled as AqI to AqIII), and three aquitards (labelled as AdI to AdIII) (Miao et al. 2007; Wang et al. 2009), as shown in Fig. 2. AdI does not extend to the analysed location. The groundwater level of the phreatic aquifer is 0.5–2.0 m below the ground surface (Shi et al. 2006). As shown in Fig. 1, the groundwater level in AqII in the analysed area is –30 to –60 m, the lowest level of the groundwater is located to the south-east of Changzhou, and this was –80 m in 2002.

### 2.2 Groundwater pumping and groundwater level

For domestic and industrial use, groundwater pumping has been conducted continually for almost 30 years in Changzhou and is still not limited in some places. Figure 3 shows the groundwater pumping volume in recent years in Changzhou. The total groundwater withdrawal volume reached  $8918 \times 10^4 \text{ m}^3/\text{year}$  in 1991, and it was mainly pumped from AqII. This uncontrolled groundwater pumping has caused large variations in groundwater head. A groundwater depression cone was located below the National Cotton Factory before 1990. The groundwater level changed from 20 m below the ground surface in the 1960s, to 51.2 m in 1975, and then to 64 m in 1981. The groundwater depression cone then moved to the south-east after 1990. Figure 4 shows the changes in groundwater level in AqII below the National Cotton Factory from 1950 to 2003. As shown in this figure, the groundwater level dropped from –10 to –75 m within the first 45 years. Since 1995, the city government has strengthened restrictions on groundwater pumping, and some deep

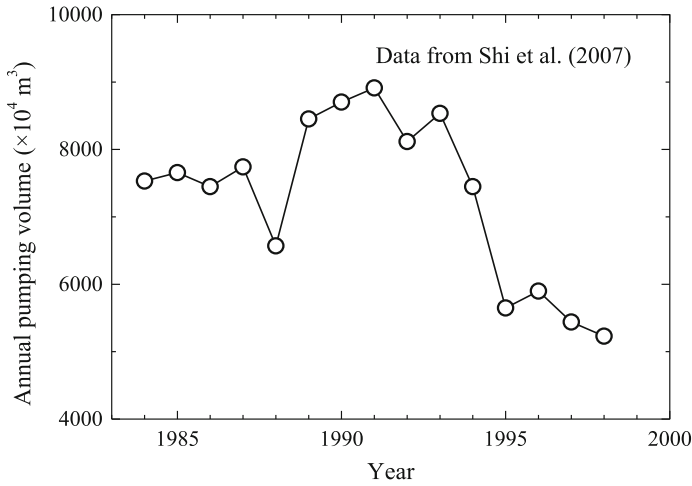


**Fig. 1** Plan view of groundwater level in AqII in 2002, Changzhou (created based on the concept of Miao et al. 2007)

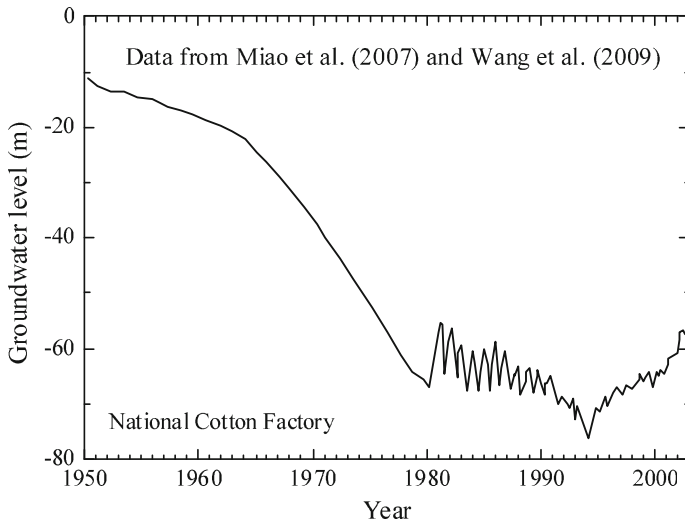


**Fig. 2** Section view of hydrogeotechnical profile within 200 m (section see in Fig. 1) (created based on the concept of Miao et al. 2007)

wells have been sealed (Wang et al. 2009). A gradual recovery of groundwater level in AqII is shown in Fig. 4. The groundwater level in AqII recovered 20 m from its lowest value in 1994 to  $-56$  m in 2003.



**Fig. 3** History of groundwater pumping from aquifers in Changzhou from 1985 to 2000

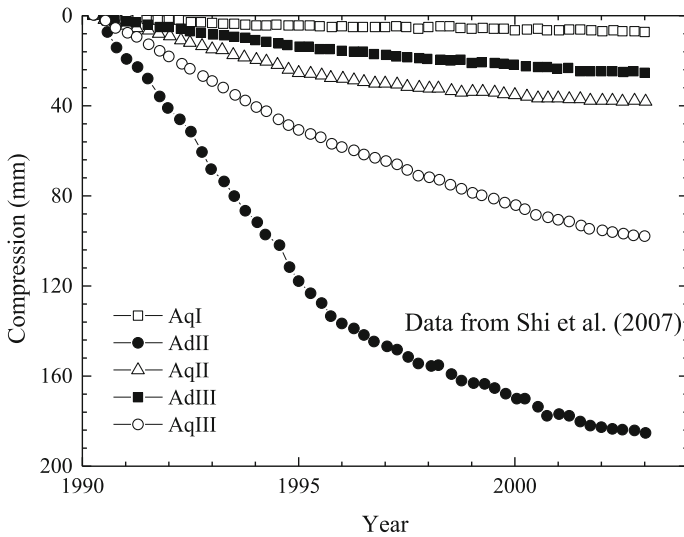


**Fig. 4** History of groundwater level in AqII in Changzhou from 1950 to 2003

### 2.3 Land subsidence and compression strata

Land subsidence was first observed in Changzhou in the 1960s (Wang et al. 2009). The average subsidence rate was 60–70 mm/year, and it reached a maximum of 147 mm/year in the mid-1980s. In the late 1980s, the land subsidence rate was maintained at 40 mm/year. After the city government enforced restrictions on groundwater extraction in 1995, the extraction rate sharply reduced, and the land subsidence rate declined to 10 mm/year in 2002.

Figure 5 shows the value of soil deformation for each compression stratum at one survey point, which is located to the south-west of Longhu Pool. AdII is the main



**Fig. 5** Compression deformation of each aquifer and aquitard in Changzhou

compression stratum, and it accounts for 58.01 % of the total land subsidence. The ratio of compression deformation of AqII to the total land subsidence is 12.35 %. The previously mentioned phenomenon indicates that although the land subsidence was mainly attributed to the consolidation of the aquitard overlying AqII, the contribution of compression deformation of aquifers to the total land subsidence cannot be ignored.

## 2.4 Prediction models

To simulate the subsidence in Changzhou City, the following three models were employed: (1) groundwater flow model (Shen et al. 2006; Shen and Xu 2011), (2) elasto-plastic model based on Cauchy mechanics (Brinkgreve 2004), and (3) modified Cosserat continuum model (Shen et al. 2013). The details of each model are introduced as follows:

## 2.5 Groundwater flow model

A groundwater flow model based on classical Cauchy mechanics was employed using the method proposed by Shen et al. (2006), in which groundwater seepage and land subsidence analysis are coupled. In this method, the basic equation for 3D groundwater flow in saturated media is expressed as follows (Shen et al. 2006; Shen and Xu 2011):

$$\frac{\partial}{\partial x_i} \left( K_{ij} \frac{\partial h}{\partial x_j} \right) - q = S_s \frac{\partial h}{\partial t} \quad (1)$$

where  $K_{ij}$  = hydraulic conductivity;  $h$  = hydraulic head;  $q$  = external source/sink flux;  $S_s$  = coefficient of specific storage;  $t$  = time.

The release of water in soil is normally due to the compression of the soil and the expansion of the water. Thus, the coefficient of specific storage,  $S_s$  is expressed as follows:

$$S_s = \gamma_w (m_v + n\beta) \quad (2)$$

where  $\gamma_w$  = unit weight of water;  $m_v$  = soil coefficient of volume compressibility;  $n$  = effective porosity;  $\beta$  = coefficient of volume compressibility of water.

On the condition that the groundwater pressure is not high, the compression of the water can be ignored, because it is very low compared with the compression of the soil, that is to say  $\beta = 0$ . The dissipation of water in soil is only due to the compression of soil. The porosity change due to the variation of hydraulic head is expressed in the following relationship (Shen et al. 2006; Shen and Xu 2011):

$$S_s = \frac{\partial n}{\partial h} = \frac{\partial n}{\partial \sigma'} \frac{\partial \sigma'}{\partial h} = \frac{\gamma_w}{1 + e_0} \frac{C'}{\sigma'} \frac{1}{2.303} \tag{3}$$

where  $n$  = porosity;  $h$  = hydraulic head;  $e$  = void ratio;  $\sigma'$  = effective stress;  $C'$  = the slope of  $e$ -log $\sigma'$  curve.

Variation of effective stress:

$$\Delta \sigma' = -\Delta u = -\gamma_w \Delta h \tag{4}$$

Compression of soil layer:

$$S_t = m_v \Delta \sigma_z H = \frac{S_s}{\gamma_w} \Delta \sigma_z H = S_s \Delta h H \tag{5}$$

where  $S_t$  = compression of soil layer.

Thus, the compression of the soil layer can be calculated based on the variation of the hydraulic head from the specific storage  $S_s$ . The value of land subsidence can be calculated by accumulating the compression of the soil layers.

The coefficient of volumetric compressibility,  $m_v$ , for clayey soil in aquitards changes with the effective stress and is expressed as (Shen and Xu 2011)

$$m_v = \frac{0.434 C'}{(1 + e) \sigma'_v} \tag{6}$$

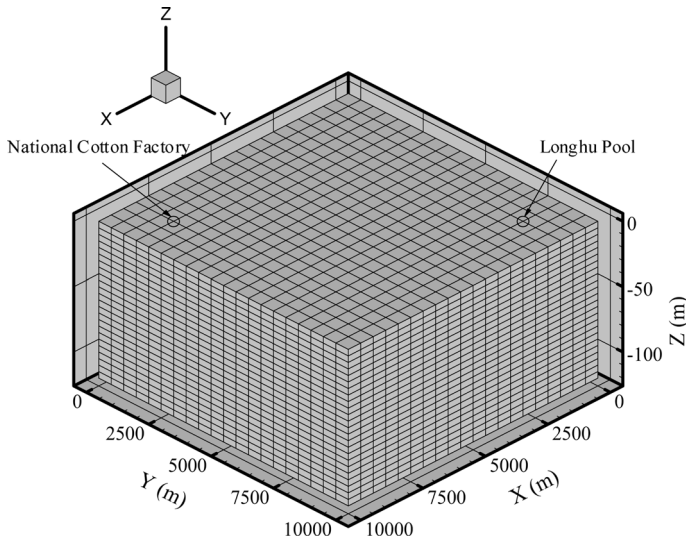
where  $e$  = void ratio,  $C'$  = slope of  $e$ -log $P$  curve (when  $\sigma' < P_c$ ,  $C' = C_s$  = unloading slope; when  $\sigma' > P_c$ ,  $C' = C_c$  = compression index).

Sandy soil in aquifers of Changzhou is in an elastic state because the change of effective stress induced by the change of groundwater level is less than its yield stress. Therefore, for sandy soil in aquifer,  $m_v$  is considered as constant values, which can be calculated from Young's modulus and Poisson's ratio as follows (Budhu 2000):

$$m_v = \frac{(1 + \mu)(1 - 2\mu)}{(1 - \mu)E} \tag{7}$$

where  $\mu$  = Poisson's ratio,  $E$  = Young's modulus.

Figure 6 shows the 3D finite element mesh in the groundwater flow model. It is 10 km by 10 km in plan. The FEM mesh in the plan is set as 500 m in size. The number of nodes and elements in each layer is 441 and 400, respectively. In the vertical direction, the analysed soil depth is 125 m, and the hydrogeology system simply includes 5 strata. The aquifer layers include phreatic aquifer, AqI, and AqII without considering the interlayers in these aquifer layers. The initial soil parameters used in the groundwater flow model are tabulated in Table 1. The initial groundwater level of phreatic aquifer and AqI is set as -2 m in 2001 according to the monitoring data (Shi et al. 2006). The groundwater level in AqII changed from -40 m in 2001 to -70 m in 2002. At the bottom, both vertical and



**Fig. 6** Three-dimensional finite element mesh in groundwater flow model

**Table 1** Parameters used in groundwater flow model

Soil layer	Buried depth (m)	$e$	$\gamma_t$ (kN/m <sup>3</sup> )	$k_v$ (10 <sup>-4</sup> m/day)	$k_h$ (10 <sup>-4</sup> m/day)	$S_s$ (10 <sup>-6</sup> m <sup>-1</sup> )	$m_v$ (10 <sup>-6</sup> kPa <sup>-1</sup> )
Phreatic aquifer	0 ~ -10	0.941	18.2	50	30	3.34	61.9
AqI	-10 ~ -25	0.841	17.5	20	10	5	23.7
AdII	-25 ~ -55	0.759	18.5	360	172	2.67	49.5
AqII	-55 ~ -115	0.923	19	2800	1360	1.14	15.8
AdIII	-115 ~ -125	0.762	18.7	140	70	2.22	33.8

$e$  = void ratio;  $\gamma_t$  = unit weight of soil;  $k_v$ ,  $k_h$  = horizontal and vertical hydraulic conductivity;  $m_v$  = soil coefficient of volume compressibility;  $S_s$  = specific storage

horizontal displacements were restrained, and the bottom line was set as undrained. The hydraulic head along the four borders is alterable to simulate the possible drawdown of the groundwater level.

## 2.6 Elasto-plastic model based on Cauchy mechanics

An elasto-plastic model based on Cauchy mechanics was employed with the finite element method (FEM) under axisymmetric stress conditions using the software package 'Plaxis'. The aquitards mainly of clay were represented by the soft soil model, which is often used to simulate the compression of normal consolidated clay in Plaxis, and the sandy aquifers were represented by an elasto-plastic model with drained condition based on the Mohr–Coulomb criterion (Yin et al. 2002, 2010, 2011; Brinkgreve 2004).

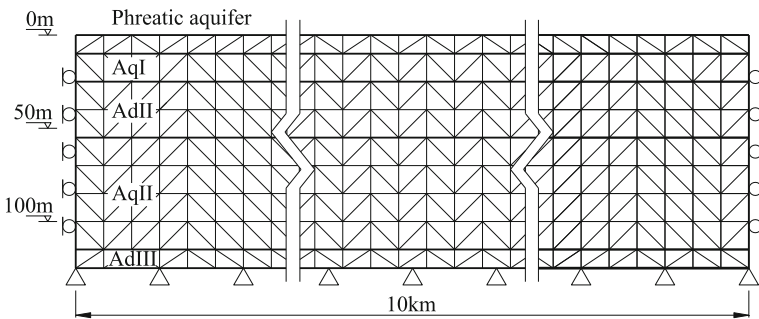


Figure 7 shows the FEM calculation model and the calculated range in the elasto-plastic model. The calculated range in plan is 10 km. The number of nodes and elements are 5010 and 900, respectively. In the vertical direction, the analysed soil includes 5 strata with a depth of 125 m. The boundary conditions used in Plaxis were the same as those used in the groundwater flow model. The relationship between drawdown of groundwater level and time was set in the same way as for the groundwater flow model. The soil parameters used in this model are listed in Table 2.

### 2.7 Modified Cosserat continuum model

To predict the deformation of aquifers in Changzhou, a modified Cosserat continuum model proposed by Shen et al. (2013) is adopted in this study. According to this approach, when there is a hydraulic gradient in the spatial domain, unbalanced forces will occur, which cause shear deformation in the vertical direction.

The total land subsidence is the sum of the deformation of aquifers and aquitards in the modified Cosserat continuum model. The modified Cosserat continuum model, namely modified Budhu’s approach (Shen et al. 2013), is used to calculate the deformation of aquifers, and the elasto-plastic model based on Cauchy mechanics is used to simulate the deformation of aquitards. Since the original Budhu’s approach is only used in an unconfined aquifer, Budhu’s approach has to be modified for this study. To apply Budhu’s approach in a confined aquifer, the following additional assumptions for confined aquifers are presented (Shen et al. 2013):



**Fig. 7** Finite element analysis mesh in the elasto-plastic model with axisymmetric condition

**Table 2** Parameter in classical Cauchy continuum model

Soil layer	Buried depth (m)	$\gamma_i$ (kN/m <sup>3</sup> )	$E$ (MPa)	$\nu$	$c$ (kPa)	$\varphi$ (°)
Phreatic aquifer	0 ~ -10	18.2	12	0.3	17	29
AqI	-10 ~ -25	17.5	38	0.2	19	32
AdII	-25 ~ -55	18.5	15	0.3	40	32.7
AqII	-55 ~ -115	19	57	0.2	3	22.5
AdIII	-115 ~ -125	18.7	22	0.3	58	28.1

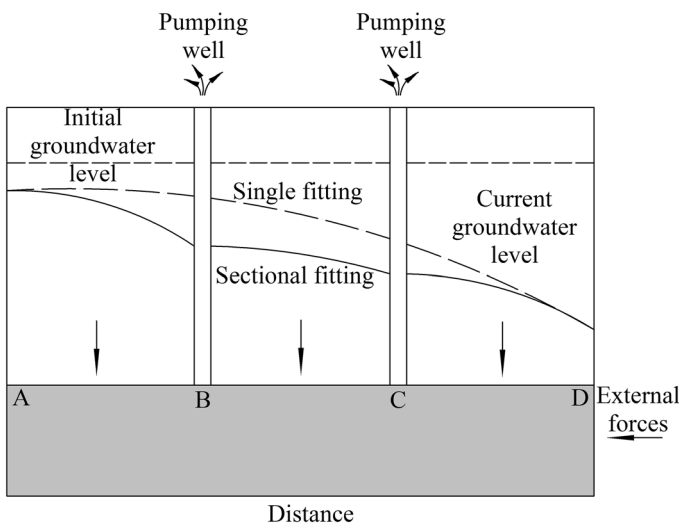
$\gamma_i$  = unit weight;  $E$  = Young’s modulus;  $\nu$  = poisson’s ratio;  $c$  = cohesion;  $\varphi$  = friction

1. A confined, isotropic, homogeneous aquifer is overburdened by an aquitard with a much lower hydraulic conductivity than that of the underlying confined aquifer (e.g. one-tenth);
2. The variation of groundwater replenishment from an aquitard depends on the consolidation rate of overburdened aquitards;
3. An aquifer is a continuous medium without cracks;
4. An overburdened load from aquitards above an aquifer remains unchanging during groundwater pumping in confined aquifers;
5. Groundwater potential at its initial state in a confined aquifer is the same throughout the horizontal direction;
6. The groundwater level declines slowly with pumping time.

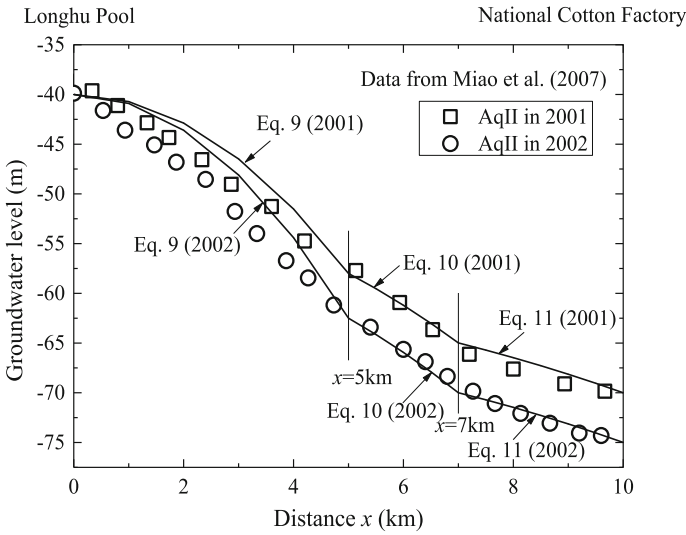
Budhu's approach was used to predict land subsidence over a distance of 800 m at a location in Arizona, USA. A single formula was used to simulate groundwater level. The analysed distance in the current study is comparatively very long, so the single groundwater level formula is not suitable. In order to apply this model to large distances, a layer of confined aquifer consisting of a uniform soil and pumped from several wells is investigated. As shown in Fig. 8, the groundwater is pumped at several locations over a long distance, which is more than 5 km, and all of the faces of this confined aquifer are set as being drained. After pumping, the water head declines spreading outwards from the cone well, but the decline is not uniform. For such a situation, the groundwater head curve is not suitable to be assumed as one groundwater level equation.

Therefore, the groundwater head curves in this modified Cosserat continuum model are assumed as the following simultaneous equations in Fig. 8:

$$\begin{aligned}
 h_w &= -(\alpha_1 x^2 + h_0) && \text{(Segment A-B in Figure 8)} \\
 h_w &= -(\alpha_2 x^2 + h_{0B}) && \text{(Segment B-C in Figure 8)} \\
 h_w &= -(\alpha_3 x^2 + h_{0C}) && \text{(Segment C-D in Figure 8)}
 \end{aligned}
 \tag{8}$$



**Fig. 8** Variation of groundwater level with distance at several wells



**Fig. 9** Simulated and measured water level of aquifer II in 2001 and 2002

where  $h_w$  is the groundwater head at increasing depths from the initial head surface at the pumping well,  $h_0$ ,  $h_{0B}$  and  $h_{0C}$  are the groundwater heads at an arbitrary selected origin,  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$  are constants, and they are changing with water level.

In this study, the depth of AqII was from  $-55$  to  $-115$  m. According to the measured groundwater level in AqII in 2001 and 2002, the groundwater head in this layer from 2001 to 2002 varied as described in the following simultaneous equations:

From 0 to 5 km,

$$\begin{cases} -7.2 \times 10^{-7}x^2 - 40 \dots (2001) \\ -9 \times 10^{-7}x^2 - 40 \dots (2002) \end{cases} \quad (9)$$

From 5 to 7 km

$$\begin{cases} -2.91 \times 10^{-7}x^2 - 50.725 \dots (2001) \\ -3.125 \times 10^{-7}x^2 - 54.6875 \dots (2002) \end{cases} \quad (10)$$

From 7 to 10 km

$$\begin{cases} -0.98 \times 10^{-7}x^2 - 60.196 \dots (2001) \\ -1.08 \times 10^{-7}x^2 - 59.716 \dots (2002) \end{cases} \quad (11)$$

The simulated groundwater level and field measurement are both depicted in Fig. 9. As shown in this figure, the groundwater level has been separated into three parts over a distance of 10 km using simultaneous equations, for both 2001 and 2002. The simulation curves fit the field data very well. In one year, the largest drawdown of groundwater level is 5 m in this location.

The parameters used in this site are as follows: (1) the character length of the model is 10 km; (2) the thickness of AqII in this location,  $l_z$ , is 60 m; and (3) the aquifer soil is elastic and isotropic with classical shear modulus  $G = 15$  MPa, and Cosserat continua shear modulus  $G_c = 7.5$  MPa.

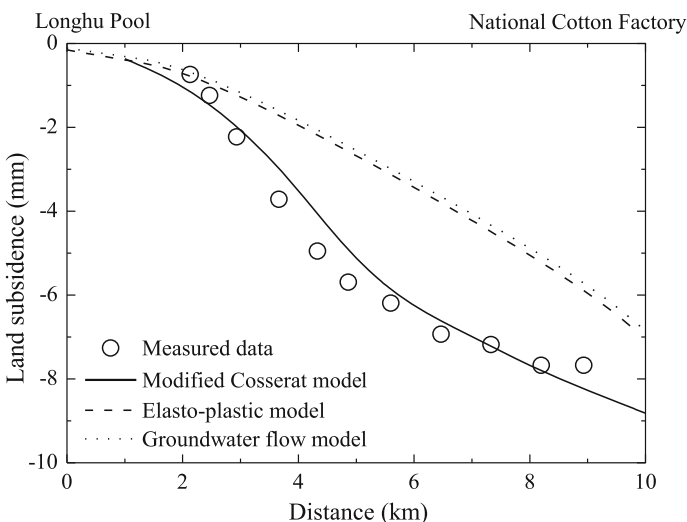
### 3 Simulated results

Figure 10 plots the measured and calculated land subsidence from Longhu Pool to the National Cotton Factory by using the above-mentioned three models. The value predicted by the groundwater flow model and the elasto-plastic model is lower than that predicted by the modified Cosserat model. As shown in Fig. 10, the result predicted by the modified Cosserat model is close to the measured data. The modified Cosserat model can therefore predict land subsidence well.

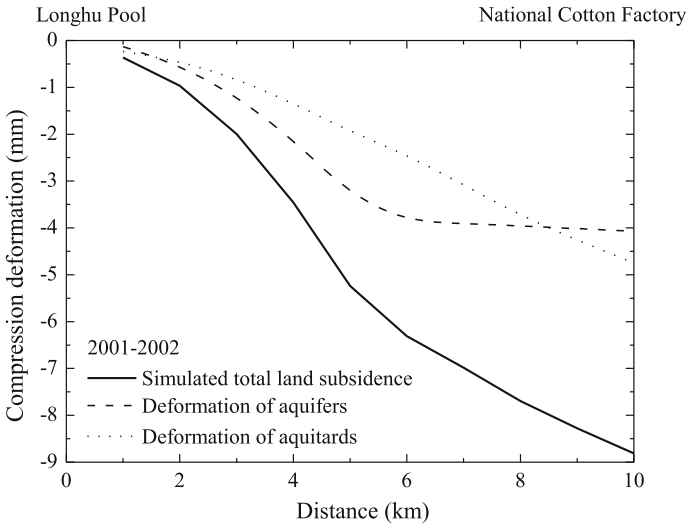
Figure 11 shows the simulated deformation of aquifers and aquitards in the modified Cosserat model. The deformation of aquifers predicted by the modified Cosserat model (Shen et al. 2013) is larger than the deformation of aquitards predicted by the elasto-plastic model based on Cauchy mechanics, for the distance from 0 to 8 km, but from 8 to 10 km, the deformation of aquifers is smaller than that of aquitards. The compression of sandy aquifers accounts for a large part of the total land subsidence. According to the results of the classical Cauchy continuum model, the compression of the aquitard accounts for most of the total settlement, and the compression of the aquifer is very small, even in a site with large groundwater level drawdown. Since the groundwater flow model and the elasto-plastic model underestimate the deformation of aquifers, the result predicted by these two models is lower than the measured data.

### 4 Discussion

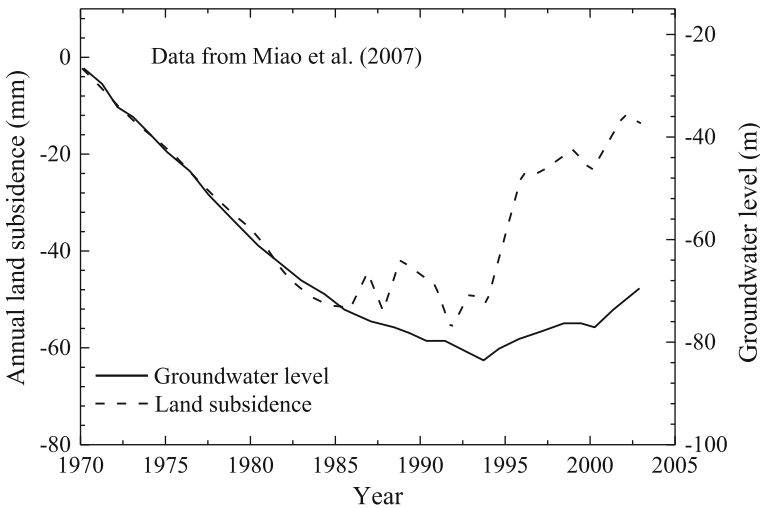
As a result of demand for water for domestic and industrial use, the groundwater level in Changzhou has been continually decreasing in the last 50 years. Figure 12 shows the variation of groundwater level in AqII and the annual land subsidence in Changzhou from 1970 to 2005. As shown in Fig. 12, the annual land subsidence has a strong correlation with the groundwater level in AqII. The water level has declined since 1970 and reached



**Fig. 10** Comparison of the annual land subsidence from the National cotton Factory to Longhu Pool

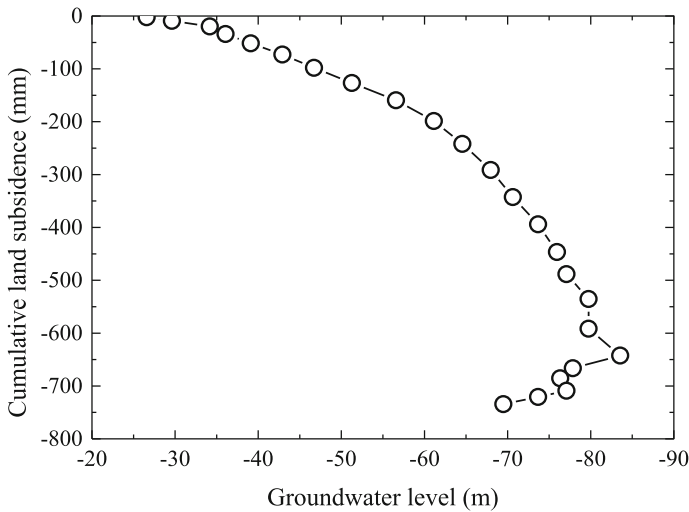


**Fig. 11** Simulated deformation of aquifers and aquitards in the modified Cosserat continuum model



**Fig. 12** Relationship between annual land subsidence and groundwater level from 1970 to 2005 in Changzhou

the lowest level in 1994. The groundwater level changed from  $-25$  to  $-85$  m within 24 years. After 1994, the groundwater level began to recover because some measures were adopted to restrict groundwater withdrawal. The variation pattern of annual land subsidence at this site is strongly connected with the variation pattern of groundwater level over 35 years. The annual land subsidence from 1970 to 1986 increased steadily. The average annual land subsidence rate has then fluctuated within a 10-mm range since 1986 and reached about 60 mm in 1992. Since 1994, because of the groundwater level recovering in AqII, the annual land subsidence rate has also recovered from  $-60$  to  $-10$  mm.



**Fig. 13** Relationship between groundwater level in AqII and cumulative land subsidence

The relationship between groundwater level and cumulative land subsidence is shown in Fig. 13. Within 35 years, the cumulative land subsidence reached 750 mm. The cumulative land subsidence increased linearly with groundwater level decline in AqII before 1994. When the groundwater level began to recover after 1994, the rate of increase of land subsidence was reducing. This phenomenon indicates that the annual land subsidence is closely correlated with the variation of groundwater level in AqII.

The drawdown of groundwater level will lead to accumulated shear stress in aquifers according to Cosserat mechanics. Since shear deformation and macro-rotation result in compression deformation of a sandy aquifer, the relationship between deformation of aquifers and drawdown of groundwater level in aquifers may be due to the progressive accumulation of shear deformation and macro-rotation with time. Therefore, the groundwater pumping in AqII caused severe land subsidence, which is underestimated by the groundwater flow model and the elasto-plastic model based on Cauchy mechanics. The combination of the Cosserat continuum model, which is used to predict deformation of aquifers, and the elasto-plastic model based on Cauchy mechanics, which is used to predict deformation of aquitards, is a useful way to predict the total land subsidence accurately.

This study exists some limitation as follows: (1) the interlayer in the aquifer layer is not considered. Internal erosion of fine silty and clay particles in the pore of aquifer sand will happen under the condition of large hydraulic gradient and increase the deformation of aquifer. (2) Associated with the groundwater pumping, a potential threat to the surrounding environment is the transport of some contaminants presented in the soils (Du and Hayashi 2006; Fan et al. 2014), which maybe impact the compression properties of the aquitard and aquifer layers. These factors should be investigated in the next research.

## 5 Conclusions

This paper has established three models to predict land subsidence caused by groundwater pumping in Changzhou. The analysed results from these three models are compared. Based on the results, the following conclusions can be drawn:

- (1) Land subsidence is due to the drawdown of groundwater level in the analysed location in Changzhou City. The relationship between land subsidence and the groundwater level of the aquifer can be interpreted using Cosserat mechanics. The drawdown of groundwater level will lead to accumulating shear stress in aquifers, according to Cosserat mechanics, and will then result in the compression deformation of a sandy aquifer. The deformation of aquifers makes a significant contribution to the total land subsidence.
- (2) Three models, including a groundwater flow model, an elasto-plastic model based on Cauchy mechanics, and a modified Cosserat model, are adopted to simulate the land subsidence in Changzhou City. Since the groundwater model and the elasto-plastic model underestimate the deformation of aquifers, the value of land subsidence predicted by these two models is lower than that predicted by the modified Cosserat model.
- (3) A 3D modified Cosserat continuum model is used to simulate land subsidence in Changzhou by considering the deformation of aquifers based on Cosserat mechanics and that of aquitards based on Cauchy mechanics simultaneously. The simulated result using this model is close to the measured data, which indicates that the modified Cosserat model can interpret the land subsidence in Changzhou well, and it is a useful approach to predict the total land subsidence accurately.
- (4) To mitigate subsidence hazards, the locations of pumping wells and the groundwater withdrawal volume from each pumping well should be planned to decrease the shear stress in the aquifers resulting from the high hydraulic gradient. A detailed protection plan should be researched further.

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