Trends And Mechanisms Of Land Subsidence Of A Coastal Plain In The Delta Of Yangtze River-China

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Abstract: The deltas of Yangtze River have been characterized with incessant occurrence of land subsidence due to over-exploitation of groundwater resources. Being the major source of water supply for industrial, agricultural and municipal development; groundwater have been ceaselessly over drafted in an area which is highly susceptible to land subsidence. Thus, this menace has wreck serious environ-geological and economical hazards in the delta of Yangtze River. 24 years data have been obtained and analyzed, using excel multivariable analysis functions to establish the trends and causes of land deformation in this area. Our results have shown that groundwater abstractions have direct correlations with land deformation except when adequate precaution and control measures were employed to ameliorate this environ-geologic hazard. However, The trends of land deformation kept increasing; showing that other causes such as construction loads due to rapid economic growth and urbanization is another vital reason for the occurrence of land subsidence in this area.

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I. Introduction

Establishing the limits of pumpage for a sustainable supply requires accurate information about the safe yield of the groundwater system. Safe yield refers to the rate at which groundwater can be withdrawn from an aquifer without causing an undesirable effect It was reported in 1995 that there were more than 150 major cities in the world where subsidence were substantial [1- 3].The affected areas, mostly coastal, include Bangkok(Thailand), Houston(USA), Mexico city(Mexico), Osaka(Japan), San Jose(USA), Shanghai(China), Tokyo(Japan), and Venice(Italy)[4]. Land subsidence accompanied with heavy withdrawal of groundwater has become a worldwide problem [5]. It has been shown by [6] that the characterization of the soil strata deformation varies from region to region because of complicated hydrostratigraphy and groundwater withdrawal. The deformation characteristics of hydrostratigraphic units depend on the types and properties of soil within the units [7]. In china, Land subsidence mainly happens in plains of Yangtze River delta, the north China plain and Fenwei graben basin. The most serious cities are Shanghai, Tianjin, Xi'an, Beijing and Ningbo etc. Some of the main destructions attributed to land deformation include; (1) deterioration in groundwater quality and Seawater Intrusion (2) reduction in the natural storage capacity of geologic strata (3) destruction of natural drainages, thus, exposing the land to flooding (4) destruction of groundwater pumping water wells and channelization distortion (5) intensifying the movement of ground fissure (6) undulation of the natural ground level (7) significant economic impact loss and so on.

A decrease in ground water level will causes an increase in effective stresses at clay layers which results consolidation of lower layers [8]. As water is withdrawn from the aquifer and the piezometric head drops, the effective stress on the aquifer increases even though the total stress remains constant. It is the increase in effective stress that causes the compression of the soil leading to subsidence [9].

Although land subsidence can result from many factors, the primary ones are human activities and geological actions, especially extensive groundwater withdrawal {[9], [10]}. Excessive ground water withdrawal, especially in unconsolidated clays can cause land subsidence and earth fissures. In recent decades, land subsidence because of its destructive results such as differential settlement and earth fissures in many part of the world, such as desert areas like Kerman province and some other parts of the world become a major consideration [11]. Land subsidence can be defined as the sinking or settling of the land surface due to any of several processes, among which fluid withdrawal is the most important {[11], [13]}.

II. Material and Method

Terzaghi's effective stress principle has been widely used when explaining the land subsidence caused by groundwater exploitation. That is the total stress of saturated soil equals effective stress between particles and pore water pressure and the deformation of soil is mainly due to the change in the "effective stress". Assuming the total stress remains constant, when groundwater table descends, the effective stress will increase and the soil will be compacted and consolidated, thus susceptible land subsides. This phenomenon and its effect become obvious especially when the soil is unconsolidated. Thus the according to [14], the basic one dimensional equation of land deformation is given in equation 1 as follow:

$$\sigma^T = \sigma^{'} + u_p \qquad (1)$$

Where σ^T is the total pressure, $\sigma^{'}$ is the effective stress and u_p is the pore water pressure

Data analysis: A data of 2 ½ decades (1984 to 2008) have been collated and statistically analyzed to study the trends and patterns of land subsidence in the study area. The data obtained from the extensometers show the amount of land deformations over this period of time. The statigraphic profile of the study area had been sectioned into 6 major layers as shown in figure 1 below

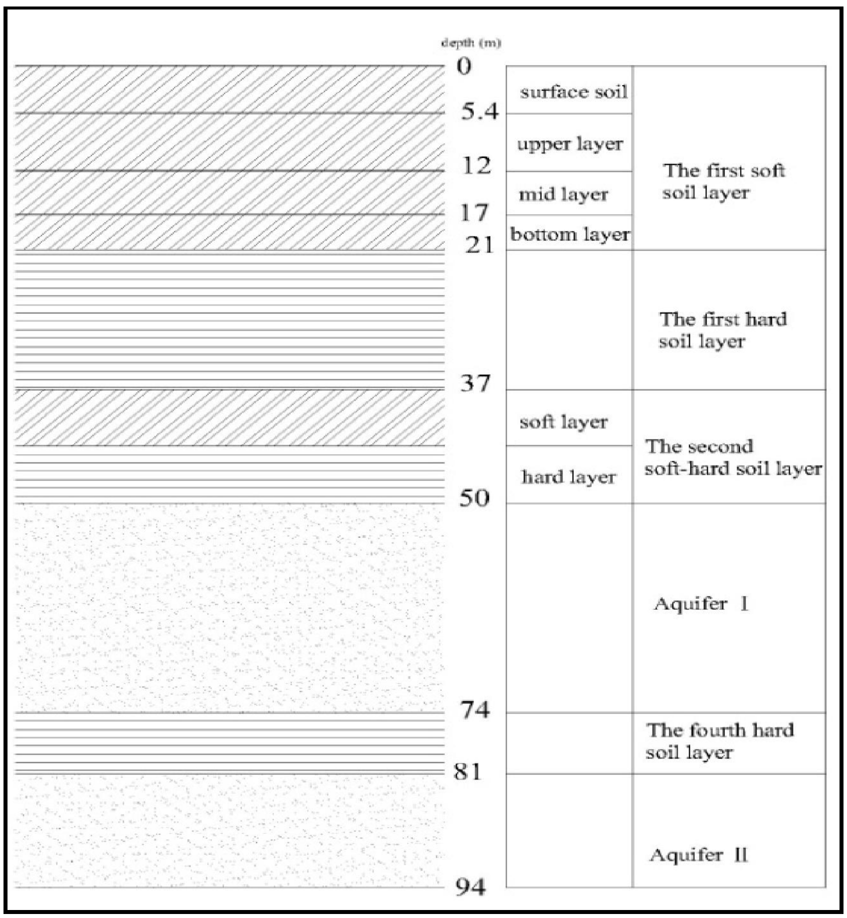

Figure 1. Depicting the lithological profile of the study area

The total depth of the strata is about 100meters from the surface level. the first soft layer clasified as layer 1 ranges from 0- 21 meters and further sub- classified into 4 minor zones based on the lithological differences; as surface soil, upper layer, mid-layer and bottom layer respectively. Similarly, the first hard soil layer categorized as the 2nd layer ranges from 21-37 meters with a single lithology. Other layers are similarly classified and as shown in figure 1. There are two basic aquifers while the other layers are aquitards with very poor yield of groundwater.

Excel functional capability in presenting the trends between multiple variables is used in our analysis to generate the correlations between groundwater levels and land subsidence by inputting data of 1984 to 2008. The general trend of land subsidence are classified into three main periods as (1) 1984- 1986, which is the regarded as the beginning period and during which no precaution or control measure in place on the exploitation of groundwater serious especially in the very vulnerable areas of the Yangtze's delta area, thus, the subsidence at the period was alarming and raising many public awareness to curtail this geo-hazard. At this period government started putting measures in place. (2) 1986-2003: government began to control the exploitation; the exploitation was strictly minimized and outlawed in some highly prone areas. Hence, land subsidence occurrence started declining during this period due to the stringent controls in groundwater over exploitations. (3) 2003-2008 marked almost the end to the incessant occurrence of land subsidence because water injection into the aquifers took place during this period; hence, the menace was kept under close and active controls at this period in time.

III. Results and Discussion

Table 1 showing monthly annual average of groundwater level, monthly average and cumulative deformations from 1984-2008

Date (Year)	**Annual average monthly groundwater level (m)**	**Annual average monthly deformation (mm)**	**Annual average monthly cumulative deformation**
1984	1.034	-0.622	-2.122
1985	1.100	-0.140	-15.033
1986	1.423	-0.850	-25.975
71987	1.237	-0.608	-34.525
1988	1.238	-0.608	-41.592
1989	1.329	-0.175	-46.450
1990	1.374	-0.275	-49.467
1991	1.357	-0.350	-52.692
1992	1.387	-0.175	-55.817
1993	1.336	-0.808	-61.975
1994	1.366	-0.833	-71.067
1995	1.196	-0. 508	-79.892
1996	1.322	-0.450	-85.825
1997	1.648	-0.508	-91.0917
1998	0.791	-0.950	-100.533
1999	0.524	-0.667	-109.808
2000	0.508	-0.775	-118.083
2001	0.578	-0.733	-128.000
2002	0.586	-0.475	-134.817
2003	0.613	-0.508	-142.250
2004	0.618	-0.467	-148.275
2005	0.609	-0.367	-153.208
2006	0.607	-0.600	-159.608
2007	0.604	-0.442	-165.183
2008	0.538	-0.392	-170.808

The general trend of land subsidence: Analysis of three basic periods from1984-1986, being classified as the early period and 1986- 2003, classified as middle year and 2003-2008, being classified as the current time have shown that land subsidence were mostly pronounced during the early period (1984-1986)(figures 2 and 3). The scenario could be attributed to early period negligence and ignorance which led to continuous over-exploitations of groundwater from vulnerable zones. Virtually nothing was done to ameliorate this problem during this period, thus the study area experienced the worst scenario during those early periods. From 1986-2003, (middle period), results of our analysis have shown a glaring reduction in land subsidence (figure 2, this was due to some drastic measures taken by the authority by prohibiting excessive exploitation of groundwater resource within the vicinity of the prone areas (figures 2 and 3 and 4). From the degree of correlations shown in table 2, aquifer I (being the most exploited aquifer) is correlated with other and table 2 clearly depicted the correlations. Aquifers and layers proximities to aquifer I show the degree of hydraulic connections and how the responsiveness of other layers to the exploitation of aquifer I. Because, the first soft layer is relatively far from aquifer I, thus, its hydraulic correlation with aquifer I is almost negligible (negative values, table 2). The period tagged as the current have further shown a steady steep and contrast in the magnitude of land subsidence even when the groundwater levels were stable (figure 3, from 2004-2008). This scenario could be attributed to construction loads due to recent urbanization and infrastructural developments.

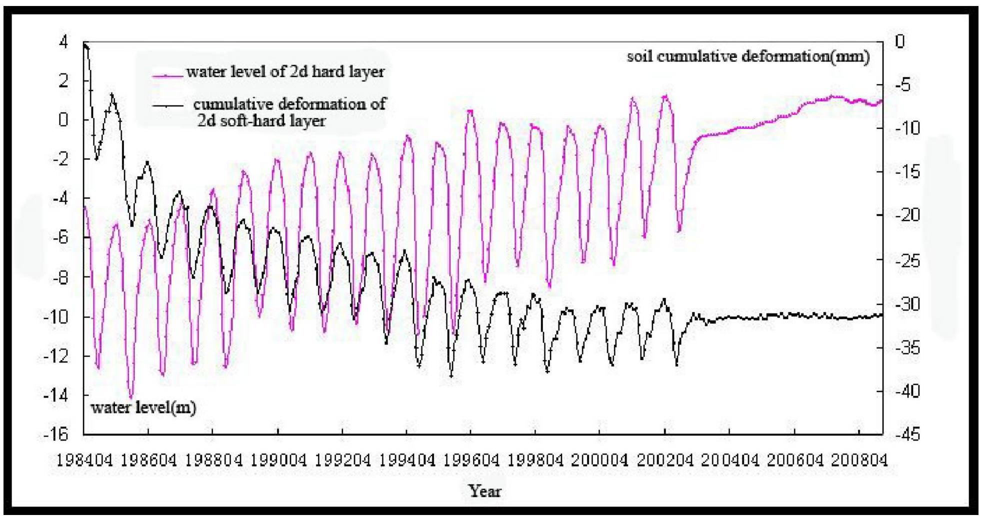

Figure 2. Cumulative deformation of Second hard layer compared with Groundwater variation of aquifer I

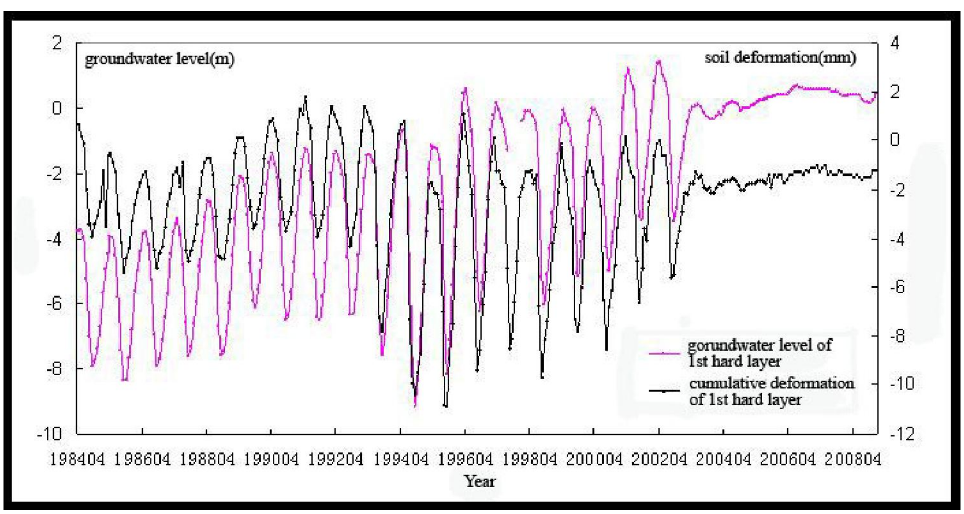

Figure 3. Cumulative deformations first hard layer compared with groundwater Variation of aquifer I

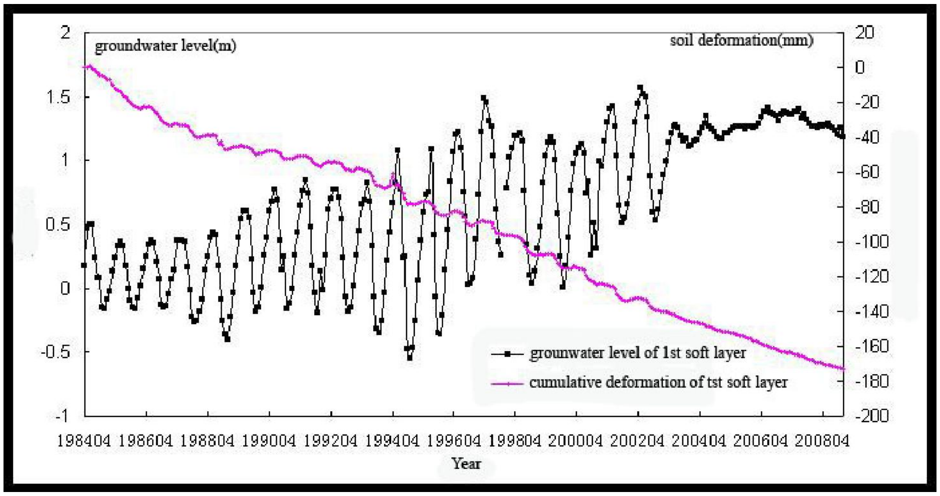

Figure 4. Cumulative deformation of First soft soil in contrast with groundwater Variation of aquifer I

Major settlement layer and Deformation characteristic of every layer:: the ratio of individual layer subsidence and total subsidence of all subsidence shows that the first soft layer contributed the biggest impacts to land subsidence by 51.5%, trailed by the second soft layer with 17.52%, and aquifer I is 16.03%, 4th hard soil layer contributes 11.5%, first hard soil layer is 2.05% and the least being aquifer II with only 1.39% contribution to the total land subsidence. The degree of settlement of each layer has informed its contributory ratio, which is a direct function of the compositional lithology of the particular layer. The empirical value of 1 for "elastic" material, less than 1 for "plastic" materials and between 0.8 and 1 for "elasto-plastic" is values adopted from field experience. Our results have shown that the first soft soil layer is plastic with ratio value of 0.23 , and first hard soil layer , and aquifer 2 are elastic with ratio value equal to 1 , while the second hard-soft soil layer, aquifer 1 and 4th hard layer with ratio value falling between 0.8 to 1 are classified as elasto-plastic.

Table 2 showing related coefficients between most exploited aquifer I and other layers

	Aquifer1	**2nd hard**	**2nd soft**	**Upper 1st hard**	**Lower 1st hard**	**1st soft layer bottom**	**Mid 1st soft layer**
Aquifer 1	1.0000						
2nd hard	0.9057	1.0000					
2nd soft	0.5531	0.7497	1.0000				
Upper 1st hard	0.8053	0.9695	0.8167	1.0000			
Lower 1st hard	0.7999	0.9674	0.8104	0.9993	1.0000		
1st soft layer bottom	0.4789	0.7581	0.9147	0.8571	0.8530	1.0000	
Mid 1st soft layer	-0.4038	-0.3624	-0.4819	-0.3492	-0.3572	-0.3036	1.0000

IV. Conclusions

The aquifer I is the most exploited one whereas other are aquitards with very little yield and every other layer except the second soft layer have direct hydraulic effect on respective aquifers according to their proximities to aquifer I (table 2 and figure 1). The mid first soft layer keeps subsiding even when the groundwater level has been carefully controlled and this would be attributed to other reasons(figures 1 to 3 and Tables 1 and 2), such as constructional load, pre-consolidation, etc. From the early period to date a direct correlation between the hydraulic level and land deformation have been established except where adequate controls are been adopted to control excessive pumping at vulnerable areas. For a sustainable hydraulic head of groundwater and economic and environmental safety, the groundwater level must be optimally exploited especially at land subsidence susceptible zones of our study place.

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