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The deformation behavior of soil mass in the subsidence region of Beijing, China

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Abstract. Land subsidence induced by excessive groundwater withdrawal has been a major environmental and geological problem in the Beijing plain area. The monitoring network of land subsidence in Beijing has been established since 2002 and has covered the entire plain area by the end of 2008. Based on data from extensometers and groundwater observation wells, this paper establishes curves of variations over time for both soil mass deformation and water levels and the relationship between soil mass deformation and water level. In addition, an analysis of deformation behavior is carried out for soil mass with various lithologies at different depths depending on the corresponding water level. Finally, the deformation behavior of soil mass is generalized into five categories. The conclusions include: (i) the current rate of deformation of the shallow soil mass is slowing, and most of the mid-deep and deep soil mass continue to compress at a more rapid speed; (ii) the sand strata behaves elastically, while the clay soil mass at different depths is usually characterized by elastic-plastic and creep deformation, which can be considered as visco-elastoplastic.

1 Introduction

Serious land subsidence problems due to excessive groundwater withdrawal have emerged in more than 150 cities all over the word (Hu et al., 2004; Tomás et al., 2010). Groundwater is the main supply source of public water in Beijing. In the past few decades, groundwater supply has accounted for approximately two-thirds of the total water supply in Beijing (Zhang et al., 2008). At the same time, some environmental geological problems arising from excessive groundwater exploitation, especially land subsidence and ground fissures, have attracted much attention. A land subsidence monitoring system in Beijing began to be constructed in 2002. In 2008, the system began collecting data from extensometers, leveling networks, InSAR and GPS surveys. The monitoring results show that by the end of 2012, the region has experienced a cumulative subsidence more than 50 mm and has affected about 4300 km^2, accounting for about 68 % of the Beijing plain area.

Many stress-strain analyses for the aquifer-system were carried out based on borehole extensometers (Burbey, 2001; Zhang et al., 2006). This paper presents a comprehensive analysis of data from the extensometers to reveal the deformation behavior of soil mass in the subsidence prone area of Beijing.

2 Deformation behaviors of soil mass at different depth

Research has shown that temporal relation patterns exist between land subsidence and groundwater withdrawal. The primary subsidence layers have gradually shifted from shallow to deeper formations (with depth more than 100 m) coinciding with the increase of the mining depth of groundwater.

F1, F2 and F3 are three subsidence stations which are equipped with a series of extensometers and, pore pressure transducers yielding groundwater level observations at different depths (Fig. 1). Generally, the Quaternary unconsoli-

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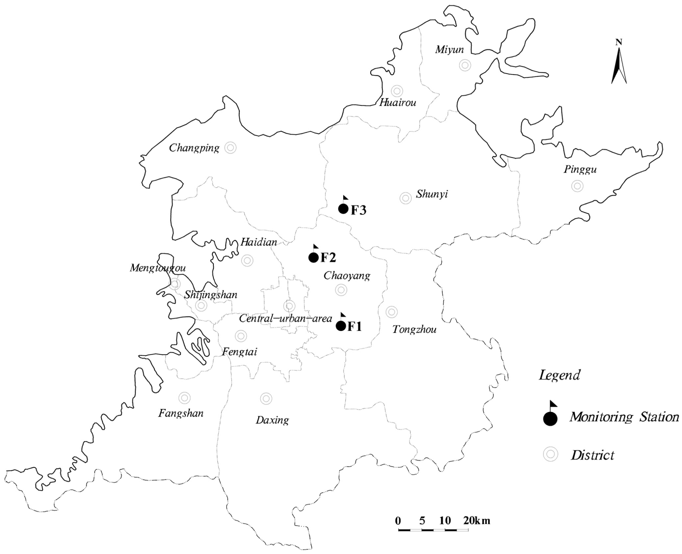

Figure 1. Location of three monitoring stations (F1, F2 and F3) for land subsidence in Beijing.

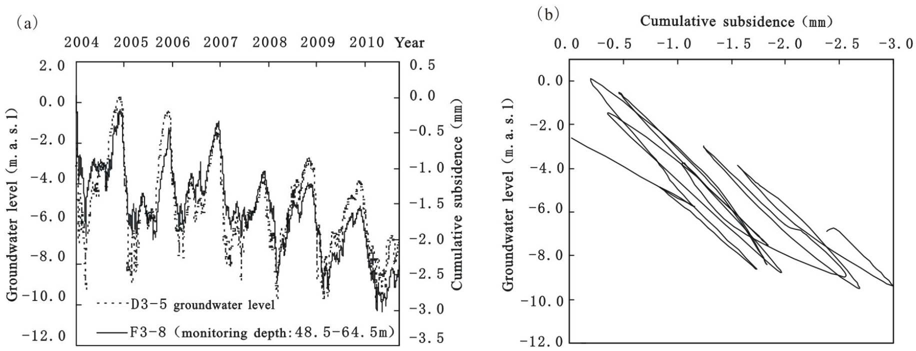

Figure 2. Deformation behavior of sand strata vs. its corresponding groundwater level at F3-8. **(a)** Groundwater level and deformation over time, **(b)** groundwater level vs. deformation hysteresis loops.

dated strata in the Beijing plain area can be divided into three compressible layers. The deformation behaviors of soil mass at different depth are explored by using stress-strain curves, obtained from the subsidence and the piezometric head data.

2.1 Sand layer

The F3-8 extensometer reveals a confined aquifer composed of fine sand and medium sand. The data shows corresponding uplift, when piezometric heads increase (Fig. 2a). The stress-deformation loops reflecting the elastic deformation feature (Fig. 2b). The annual deformation is less than 0.5 mm.

2.2 The first compressible layer

The F3-10 extensometer reveals that the shallow strata are mainly composed of silt. The annual average groundwater level fluctuates slightly (Fig. 3a). This layer subsides continuously and the deformation rate slows with time. Figure 3b shows that the compression continues whether the changes in the annual groundwater level in the phreatic aquifer. This layer is dominated by silt and behaves plastically with time-dependent creep deformation. The stress-deformation loops after 2008, showing that the deformation is elastic.

2.3 The second compressible layer

The F1-3 extensometer collects deformation data from the second compressible layer which is composed of inter-bedded clay and sand layers. The cumulative thickness of the clay layers is similar to that of the sand layers. The variation in groundwater levels implies that the effective stress is continuously increasing (Fig. 4a). Figure 4b shows that the layer compress when the groundwater level declines, however, no uplift is observed in the compression record when water levels increase. This layer shows plastic deformation with greater residual subsidence, time-dependent creep deformation and a significant visco-elasto-platic behavior.

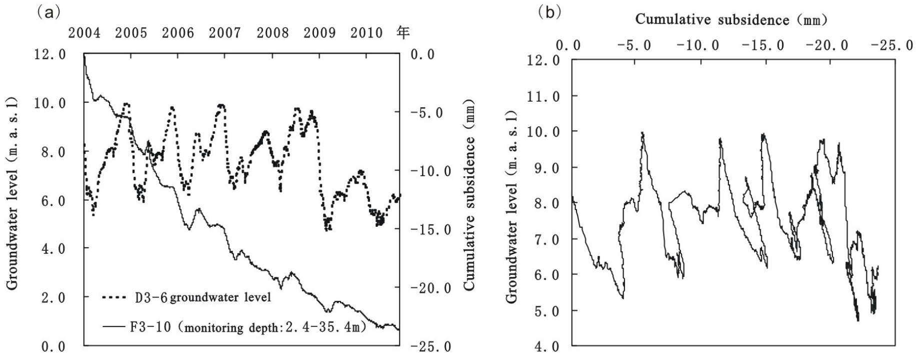

Figure 3. Deformation behavior of shallow soil mass vs. its corresponding groundwater level at layered mark F3-10. **(a)** Groundwater level and deformation over time, **(b)** groundwater level vs. deformation hysteresis loops.

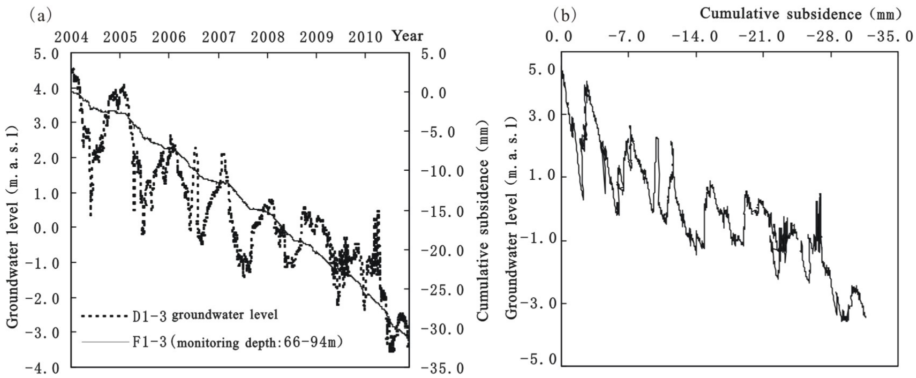

Figure 4. Deformation behavior of the mid-deep soil mass vs. its corresponding groundwater level at layered mark F1-3. **(a)** Groundwater level and deformation over time, **(b)** groundwater level vs. deformation hysteresis loops.

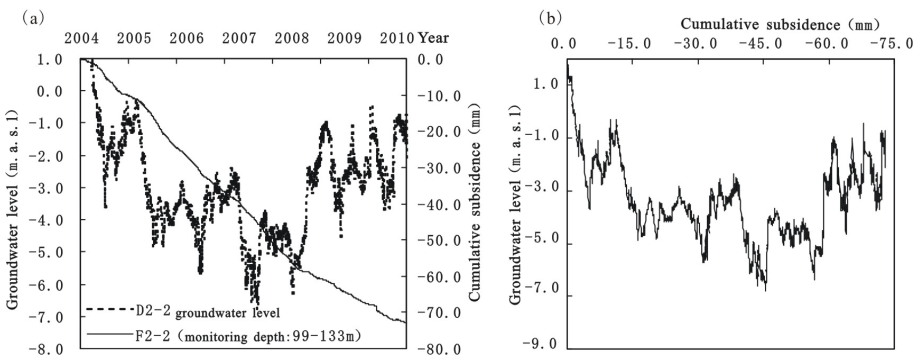

Figure 5. Deformation behavior of the deep soil mass vs. its corresponding groundwater level at layered mark F2-2. **(a)** Groundwater level and deformation over time, **(b)** groundwater level vs. deformation hysteresis loops.

2.4 The third compressible layer

The F2-2 extensometer monitors a thick clay layer in the upper part accounting for 75 % of the total thickness of this layer. The groundwater level declined from 2004 to August 2008 and then increased. Initially, the layer continuously compressed regardless of whether the groundwater level increased or declined, and subsequent to 2008 the compression rate decreased (Fig. 5a). The deformation is in the plastic range and creep deformation reveals an obvious lag effect (Fig. 5b). The compression shows obvious lag effect with the changes in groundwater level.

The F3-3 extensometer monitors the deformation of the layer composed of thick silts and clays with a cumulative thickness accounting for 80 % of this layer. The groundwater level of this layer continuously declines and behaves plasti-

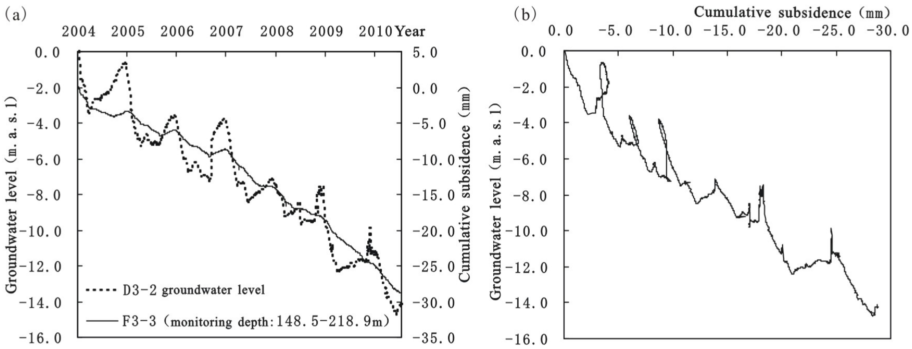

Figure 6. Deformation of the deep soil mass vs. its corresponding groundwater level at layered mark F3-3. **(a)** Groundwater level and deformation over time, **(b)** groundwater level vs. deformation hysteresis loops.

cally, while creep is largely elastic with visco-elasto-platic features (Fig. 6).

The above reveals the different deformation patterns associated with different groundwater levels at different depths. The deformation occurs mainly in the second compressible layer. In recent years, the discharge from the deep aquifers drastically increased, and the groundwater level has subsequently declined. The deformation of the third compressible layer accounts for the greater quantity of the total land subsidence in the region.

3 Conclusions

Five deformation patterns exist for different depths and groundwater change patterns in land subsidence region of Beijing. The sandy layer shows elastic deformation. The clay layers at different depths show elastic, plastic and creep deformations with visco-elasto-platic features. The deformation is controlled by the thickness of the compressible deposit, lithology and the physical and mechanical properties when the pattern of groundwater level change is provided. The deformation of the first compressible layer accounts for least amount of total land subsidence. Most of the deformation occurs in the second and third compressible layers.

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