Characterizing the Deep Pumping-induced Subsidence Against Metro Tunnel Using Vertically Distributed Fiber-Optic Sensing

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Characterizing the deep pumping-induced subsidence against metro tunnel using vertically distributed fiber-optic sensing

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Abstract: Continuous pumping of groundwater will induce uneven ground settlement, which may adversely affect the nearby metro tunnels. In this paper, taking Nantong Metro Line 1 crossing Nantong Port Water Plant as an example, the surface level measurement and subsurface deformation monitoring using vertically distributed fiber-optic sensing are implemented to acquire the surface and subsurface settlement of emergency water supply conditions. The fiber optic cable vertically buried in the constant-temperature layer is used to measure the subsurface strain field and deduce the deformation amount of each stratum. The monitoring results show that, during the pumping, the deformation of the aquifer and ground surface is linearly compressed with time; after the pumping, the ground surface continues to settle linearly at a slower rate for about 50 days, followed by a slow linear rebound, and the aquifer is logarithmically rebounded. In addition, deep pumping causes the deformation of the aquifers to be much greater than the surface settlement; the surface settlement lags behind the settlement of the aquifer by 1 to 2 months; the surface rebound recovery also exhibits a similar delay. Fitting models were derived to predict the maximum settlement and curvature radius of the site, which indicates that the adverse effects against the metro tunnel are not negligible once the continuous pumping exceeds 15 days. Those insights can be referred by the practitioners for the control of urban subsidence.

Keywords: Deep pumping; Differential settlement; Metro tunnel; Distributed fiber-optic sensing (DFOS); Space-time matrix.
1. INTRODUCTION

Ground subsidence is a hazardous environmental geology issue which not only reduces stratum elevations but also yields damage to buildings and infrastructure (Herrera-García et al., 2021; Pacheco-Martínez et al., 2013). Moreover, for metro tunnels, one of the most common linear underground infrastructures in cities, the longitudinal differential deformation induced by ground subsidence can lower their safety, durability, and waterproof performances (Peng et al., 2017; Wang et al., 2016). The variation of the groundwater level induced by human activities is a major cause of differential subsidence in urban areas (Edalat et al., 2020; Xu et al., 2016b; Xue et al., 2005). Particularly, for those cities which have to withdraw underground water as the water supply, long-term pumping activities in the water source area might induce serious subsidence problems (Chai et al., 2004; Othman and Abotalib, 2019).

Given the differential settlement, former studies mainly focused on its impacts on surface buildings. However, recent studies of ground subsidence against metro tunnels have revealed that, compared with the negative impacts imposed by the settlement of ground surface, those induced by the subsurface deformation are more significant for underground infrastructures (Shen et al., 2014). Zheng et al. (2014) studied the stratified settlement caused by the extraction of confined water using field tests and found that the deformation of phreatic layers is less than that of the confined aquifer layers, which was other than the acknowledged settlement law caused by dewatering of ground surface. Note a growing consensus has suggested that ground subsidence occurs lagging behind the pumping activity (Kearns et al., 2015), and the duration of land subsidence induced by deep pumping is longer than that by surface pumping (Cui and
However, current theoretical models of the pumping-induced settlement remain unavailable to fully characterize the abovementioned influencing factors (Budhu and Adiyaman, 2010; Wang et al., 2018; Xu et al., 2012; Zhang et al., 2017; Zhou et al., 2017). Therefore, concerning extracting deep groundwater scenarios, current models still have to be deliberately calibrated by the field measurements (Shen and Xu, 2011; Xu et al., 2016a).

As is known, the ground subsidence can be monitored by a variety of measures (Poland et al., 2006), such as leveling (Abidin et al., 2001), GPS (Baldi et al., 2009; Choudhury et al., 2018; Hu et al., 2006; Mousavi et al., 2001), InSAR (Calderhead et al., 2011; Motagh et al., 2017), and their combinations (Galloway and Burbey, 2011; Saleh and Becker, 2018). Note all those measures cannot acquire layered subsidence measurements; even the layered marks can acquire, in that the layered settlement meters are fixed-point arranged, the discrete subsidence measurements cannot finely characterize the subsurface deformation field (Jiang et al., 2016). The distributed fiber-optic sensing (DFOS), a novel monitoring technique, can obtain the strain field along the sensing cable. Although the DFOS has been employed to monitor the subsurface deformation field of Shengze, an abnormal post-dewatering subsiding area in Suzhou of China (Gu et al., 2018; Zhang et al., 2018), however, few works have been documented to use DFOS to monitor the variation process of the subsurface deformation field during a rapid pumping, no mention assess its negative impacts against metro tunnels.

In this paper, taking a groundwater plant near Nantong Port, Jiangsu Province of China, as an example, a test of deep multi-well dewatering was implemented to verify the applicability and feasibility of the DFOS technique to monitor the variation of the subsurface deformation
field. Feature extraction on the DFOS measurements was also performed to assess the impacts of subsurface settlement against the metro tunnel. Fitting equations were deduced to shed light on the evolutionary trend of the surface and subsurface deformation field during and after the pumping, which can be used to predict its long-term impacts against the metro tunnel.

2. PRINCIPLE OF DISTRIBUTED FIBER-OPTIC SENSING (DFOS)

A variety of DFOSs can be used for strain field monitoring (Zhang et al., 2014). Typically, the Brillouin optical time-domain reflectometer (BOTDR) is used in this paper. The principle of the BOTDR is based on the change in the scattered light caused by nonlinear interactions between the incident light and the phonons which are thermally excited within the light propagation medium. When occurring in an optical fiber, the backscattered light experiences a frequency shift (the Brillouin frequency), which is dependent on the temperature and strain environment of the fiber (Wu et al., 2015). Compared with other scattered lights, a substantial advantage of Brillouin scattering is that its frequency shift caused by temperature is only 0.002 %/°C, which is much smaller than that caused by strain. Therefore, while measuring the Brillouin frequency shift induced by strain, the influence of the temperature on the Brillouin frequency shift can be neglected if the changes of temperature are within 2 °C. The relationship between the Brillouin frequency shift and the strain of optical fiber yields:

\[ v_B(\varepsilon) = v_B(0) + \frac{dv_B(\varepsilon)}{d\varepsilon} \varepsilon \]  

where \( v_B(\varepsilon) \) is the Brillouin frequency against strain \( \varepsilon \), \( v_B(0) \) is the Brillouin frequency shift without stain, \( \frac{dv_B(\varepsilon)}{d\varepsilon} \) is the strain coefficient, and the proportional coefficient of strain, at a wavelength of 1.55 μm, is approximately 0.5 GHz/%.
Following such a term, the strain distributed along the sensing optical fiber can be measured. Given the monitoring scenario of land subsidence, the deformation field along the sensing optical cable caused by soil compression or rebound at depth $h$ can be calculated in accordance with the measured strain, which yields:

$$\Delta d = \int_{h_1}^{h_2} \varepsilon(h) dh$$  \hspace{1cm} (2)

In this paper, a metal-reinforced single-core cable (MRC) was used to measure the subsurface deformation, whose structure is shown in Fig. 1. The MRC, which can effectively protect the optical fibers with several metal reinforcers, has good coupling and uniformity with soil due to the screw structure of the sensor surface (Gu et al., 2018), the type of MRC in this test is NZS-DSS-C02.

![Fig. 1. The structure of a metal-reinforced single-core cable (MRC).](image)

Note DFOS acquires mass strain measurements; to efficiently extract the morphological distributions along with the underground depth, the measurements ought to be organized in the form of a space-time matrix $B$ (Sun et al., 2014). Given that the total number of sampling points
along the optical fiber is $n$ and the total number of sampling times is $m$, $B$ is a two-dimensional matrix with $n$ rows and $m$ columns, which yields:

$$
\begin{bmatrix}
\varepsilon_{00} & L & \varepsilon_{j0} & L & \varepsilon_{m0} \\
\varepsilon_{01} & L & \varepsilon_{j1} & L & \varepsilon_{m1} \\
\varepsilon_{02} & L & L & L & L \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\varepsilon_{0m} & L & \varepsilon_{jm} & L & \varepsilon_{mm} \\
\end{bmatrix}
$$

(3)

where the element $\varepsilon_{ij}$ is the measurements of the strain field on the measuring point with different depth $i$ at sampling time $j$.

Now that using the DFOS for subsidence monitoring, the submatrix $B_s$ of the space-time matrix $B$ is usually extracted to characterize the local distribution of stratum deformation field, which yields:

$$
\begin{bmatrix}
\varepsilon_{ss} & L & \varepsilon_{js} & L & \varepsilon_{ms} \\
\varepsilon_{si} & L & L & L & L \\
\varepsilon_{sj} & L & \varepsilon_{ji} & L & \varepsilon_{mj} \\
\varepsilon_{st} & L & L & L & L \\
\varepsilon_{sm} & L & \varepsilon_{jm} & L & \varepsilon_{mm} \\
\end{bmatrix}
$$

(4)

where the time interval of sampling points of the submatrix $B_s$ is $[u, v]$, and that of the sampling depth interval is $[s, t]$. The submatrix $B_s$ can also be represented as a column vector group, which yields:

$$
B_s = \begin{bmatrix} E_u \end{bmatrix}
\begin{bmatrix} E_{u+1} \\ E_j \end{bmatrix} L \begin{bmatrix} E_j \end{bmatrix} L \begin{bmatrix} E_s \end{bmatrix} L
$$

(5)

where

$$
E_j = \begin{bmatrix} \varepsilon_{j0} & L & \varepsilon_{j1} & L & \varepsilon_{j2} \\
\varepsilon_{j1} & L & \varepsilon_{j2} & L & \varepsilon_{j3} \\
\varepsilon_{j2} & L & L & L & L \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
\varepsilon_{jm} & L & \varepsilon_{jm} & L & \varepsilon_{jm} \\
\end{bmatrix}
$$

(6)
The column vector \( \mathbf{E}_j \) represents the strain vector acquired by the DFOS at the depth range \([s, t]\) at sampling time \(j\). The column vector \( \mathbf{E}_j \) at a certain time is substituted into Eq. (2) to obtain the ground deformation \( \Delta d \) at a specific depth range \([s, t]\), which yields:

\[
D d_{s,t} = \hat{\Omega}_h \int_0^h \epsilon_{ji} dh_i
\]

where \(h_i\) is the length of a certain measured micro-element section of the DFOS in the formation.

3. Pumping test

3.1 Conditions of engineering geology and hydrogeology

Nantong, a coastal city in eastern China, has planned to build four metro lines. Among those, the planned section between the Jianghai Avenue Station and the Bus Station of Metro Line 1 will travel beneath the emergency water source of the Nantong Port Water Plant. The tunnel has a circular section with a burial depth of 21 m. The lining structure has an inner diameter of 5.5 m and a thickness of 0.35 m. In accordance with the relevant specifications (Gao et al., 2010), the cumulative settlement of the layer where the tunnel is located should not exceed 20 mm, and the curvature radius of the longitudinal deformation curve is not less than 15,000 m. Given the emergency water supply, a large amount of groundwater will be extracted from the aquifer. This may induce subsidence within the overlying strata, which might in turn pose some threats to the operational safety of the metro. This paper characterizes the adverse impacts of emergency pumping on the metro tunnel by monitoring the subsurface deformation field induced by a test of multi-well dewatering.
Nantong is located in the alluvial plain of the Yangtze River Delta, widely covered by the Quaternary strata. The thickness of the strata ranges from 200 to 360 m, which is composed of a set of multiple sedimentary cycles with alternating sand and clay layers. The pumping test was performed on the south bank of the estuary of the Tonglv Canal into the Yangtze River, as shown in Fig. 2. The geographic location of the testing site is 32°00'55"~32°01'16" North latitude and 120°49'11"~120°49'33" East longitude, with a site altitude of about 4.0 m. Nantong has a humid subtropical monsoon climate with an annual average temperature of 16 ℃, precipitation of 1036 mm, and evaporation of 1392 mm.

Fig. 2. Location of the test site.

Table 1 lists the physical and mechanical parameters of the strata of the test site according to the preliminary investigation works. As seen from the table, the strata are mainly composed of sandy soils mixed with silty clayey soils. Among those, the silt layer at a depth of 50 m attains a great amount of water content, as well as a small compression modulus. The permeability varies between the silty clay and silty sand interlayers within both ranges of 120 to 150 m and 180 to 190 m. Note both interlayers might impede the transit of groundwater,
which causes the inconsistency between the deformation fields of the subsurface and the ground surface.

Table 1. Physical and mechanical parameters of soils.

| Soil layer     | Depth (m) | w (%) | $G_s$ (kN/m$^3$) | $\rho$ (kN/m$^3$) | $E_s$ (MPa) | c (kPa) | $\phi$ (°) |
|----------------|-----------|-------|------------------|-------------------|-------------|---------|-----------|
| Filling        | 5         | 28.2  | 2.7              | 18.2              | 9.1         | 14.1    | 17.6      |
| Silty sand     | 30.3      | 22.5  | 2.7              | 19.6              | 13.9        | 6.4     | 26.8      |
| Silty clay     | 49.5      | 32.7  | 2.2              | 15.7              | 7.8         | 15.4    | 19.8      |
| Medium sand    | 116.5     | 18.3  | 2.7              | 19.6              | 16.4        | 2.4     | 32.7      |
| Silty clay     | 133.0     | 23.8  | 2.7              | 20.0              | 10.9        | 43.6    | 20.6      |
| Fine sand      | 146.5     | 20.7  | 2.7              | 19.4              | 13.5        | 3.0     | 32.2      |
| Clay           | 181.0     | 22.6  | 2.7              | 19.8              | 11.4        | 110.4   | 22.7      |
| Fine sand      | 187.9     | 21.8  | 2.3              | 17.3              | 21.3        | 16.9    | 31.7      |
| Silty clay     | 193.2     | 24.8  | 2.3              | 17.0              | 14.2        | 3.3     | 31.2      |
| Medium sand    | 225.5     | 19.8  | 2.7              | 19.0              | 11.8        | 3.4     | 31.5      |
| Clay           | 230.0     | 20.7  | 2.8              | 20.8              | 14.4        | 116.1   | 20.3      |

The groundwater is mainly pore water, mostly stored in sand layers. In accordance with the storage condition, the groundwater can be divided into five aquifer groups from top to bottom, namely, the phreatic aquifer (PA), the 1st confined aquifer (CA1), the 2nd confined aquifer (CA2), the 3rd confined aquifer (CA3) and the 4th confined aquifer (CA4). Note that only CA4 is not included in this test.

The PA consists of the silty clay, silty sand, and fine sand of the Yangtze Delta phase of Holocene ($Q_h$), buried upon a shallow depth of 50 m. The depth of the water level, seasonally varying from 1 to 3 m, is affected by the atmospheric precipitation and surface runoff. The layer of PA is characterized by the coarse particles in the upper and lower sections and fine particles in the middle section along the vertical direction; some sections of the lower aquifer are
connected to CA1. The dewatering amount of a single-well is about 10~20 m$^3$/d, with poor
water quality and thus few exploitations.

The CA1 consists of alluvial and marine loose sands of the Upper Pleistocene (Q$_{p3}$), with a
burial depth ranging from 50 to 110 m. The lithology of the aquifer mainly consists of pebbles,
gravel, coarse sand, medium sand, fine sand, and silty sand; those soil particles, from coarse to
fine, are vertically distributed from bottom to top. The aquifer has high permeability and thus
enough groundwater supply, which is closely connected to the upper aquifer PA and lower
aquifer CA2. The dewatering amount of a single-well is about 2000~3000 m$^3$/d, also with poor
water quality.

The CA2 consists of the fine sand and silty sand layers of the fluvial and estuarine
sedimentary of Middle Pleistocene (Q$_{p2}$), buried from 130 to 150 m. Note the water barrier
between CA1 and CA2 is partially missing. The dewatering amount of a single-well is about
300~3000 m$^3$/d, still with poor water quality.

Aquifer CA3 consists of gravelly medium sand, fine sand, and locally gravelly cobble of
river-lake sedimentary of the Lower Pleistocene (Q$_{p1}$), whose buried depth ranges from 180 to
240 m, with an uneven thickness ranging from 20 to 100 m. The dewatering amount of a single-
well is generally over 2000 m$^3$/d. Both the quality and quantity of the groundwater are good
and rich, which makes CA3 the main exploited freshwater aquifer of Nantong city. Note that
in this test, the groundwater is extracted from aquifer CA3, with a well depth of 225 m.
3.2 Test layout and schedule

Fifteen pumping wells, labeled from W1 to W15, of the Nantong Port Water Plant near the metro line 1 were selected for this test. All wells were pumped at a rate of 80 t/h under the emergency water supply conditions, from August 9 to 15, 2018. The layout of the pumping wells and monitoring points is shown in Fig. 3. Two well groups exist in the test site, namely the south well group, W1 to W7, located near the water plant on the southern side, and the north well group, W8 to W15, at the river bank on the northern side. In addition, 23 monitoring points of ground surface settlement, labeled as S1 to S23, were deployed near the metro line and both pumping well groups.

Given the subsurface deformation field might vary from that of the surface ground, a borehole (D1), with a depth of 230 m and a diameter of 129 mm, was deliberately drilled and a metal-reinforced single-core cable (MRC) was laid inside to measure the vertical subsurface deformation.
deformation field. Fig. 4 illustrates the measuring layout of the DFOS monitoring system. The end of the MRC was connected to a BOTDR interrogator, which can process and record the strain field data along with the optical cable. The parameters of the interrogator are listed in Table 2. Before the pumping, the borehole was backfilled with special fillings to make the MRC fully couple with the surrounding soils. To synchronize the deformation of fiber with the subsurface strata, fine sand-clay soft aggregate, similar to the site strata, was used for the backfill material in the borehole. The deformation modulus of the backfill soil was adjusted with different ratios of fine sand and clay, and the backfill soil with the same deformation modulus to the surrounding strata at different depths in the borehole (Zhang et al., 2020). The instrument was calibrated at the site after the cable having been fully coupled with the strata.

Fig. 4. The layout of subsurface deformation monitoring.

Table 2. Parameters of the BOTDR interrogator.

| Model | Resolution | Accuracy | Range | Distance | Operating wavelength | Scanning interval |
|-------|------------|----------|-------|----------|----------------------|------------------|
| AV6419 | 0.05 m     | ±10 με   | ±15000 με | 0.5 km   | 1550±5 nm            | 5 MHz            |
Three monitoring items, including water level, surface settlement, and subsurface deformation field, were performed during the test. The monitoring of the water level of the wells was implemented until no obvious variation can be observed. Three leveling calibrations were conducted before pumping on June 11, June 28, and July 17, 2018, respectively. Meanwhile, three rounds of DFOS measurements were acquired for calibration on Nov. 21, Dec. 25, 2017, and Jan. 16, 2018, respectively. The monitoring schedule is depicted in Table 3. Note that three rounds of DFOS measurements were collected per occurrence date.

| Period      | Leveling                        | DFOS                  |
|-------------|---------------------------------|-----------------------|
| Pumping     | Aug. 10; Aug. 13; Aug. 15       | Aug. 9~15             |
|             | Aug. 18; Aug. 24; Aug. 30; Sep. 11; Sep. 28; | Aug. 16; Aug. 30; Sep. 5; Sep. 22; |
|             | Oct. 15; Oct. 26; Nov. 17; Nov. 29; | Oct. 10; Oct. 25; Nov. 13; |
|             | Dec. 11; Dec. 23, 2018; Jan. 4; Jan. 16, 2019 | Dec. 27, 2018; Jan. 20, 2019 |

4. Measuring results

4.1 Water level variation

From Aug. 9 to 15, 2018, the group pumping was conducted synchronously on the 15 wells in Fig. 3. After stopping pumping for 30 days, the water level tended to be stable. The measurements exhibit that before pumping, the initial water levels of the 15 wells were almost the same, approximately -16.1~17.5 m. The water level sharply dropped during the pumping; the decline rate of water level gradually slowed. The water level attained its minimum on the sixth day of pumping. Fig. 5 (a) shows the distribution of the water level. As noted from the figure, a total level drop of 11.39~16.50 m occurred on Aug. 15. Subsequently, a sharp rebound of water level occurred on Aug. 16 right after the pumping; while the round rate obviously
slowed down from Aug. 22. On August 30, 15 days after the pumping, the water level was almost restored to its initial value, only with a level falling of 0.05~0.65 m. The distribution of the recovery values of water level is shown in Fig. 5(b). As seen from Fig. 5, the greatest decline of the water level occurred near the center of the northern wells (W13), which is located near both the river bank and the metro line. Note the rise and drop of water level exhibit similar distribution patterns, suggesting the soil permeability of the west side is greater than that of the east side, and the groundwater on the east side attains a stronger rechargeability.

Fig. 5. Water level variation.

(a) Distribution of water level on Aug. 15;
(b) Distribution of water level recovery on Aug. 30.

4.2. Surface settlement

Fig. 6 shows the distribution patterns of the ground surface settlement, in which Fig. 6 (a) and (b) exhibit those during the pumping. As seen from Fig. 6 (a), at the initial stage of pumping, a large settlement occurred on the west side of the north well group; and also, a small range of settlement occurred in the south well group. The greatest settlement occurred at the measuring point S9, with a settlement value of 2.9 mm. Tiny settlement occurred on the rest part. As seen
from Fig. 6 (b), with the continuous pumping, a small amount of settlement appears on the wide
range of the site, and the settlement area of the west side of the north well group enlarged a
little. The maximum of settlement occurred on measuring point S22, with a settlement value of
3.1 mm. In addition, the settlement values of the east side of the embankment and the south
well group are both small, suggesting a plenty supply of groundwater.

Fig. (7) shows the distribution pattern of settlement within the five months after the pumping.
As shown from Fig. 7(a), within two weeks after the end of pumping, the settlement range
further enlarged, and the maximum settlement, with a value of 3.3 mm, occurred on measuring
point S23, the west side near the embankment, suggesting that the settlement behavior lagged
the deep pumping activity. As seen from Fig. 7 (b), the settlement area gradually merged to
exhibit a large range of the settlement area, which is similar to the distribution pattern of the
variation of water levels in the wells. A large settlement occurred on the west side of the north
well group and the distribution is continuous. The maximum of the settlement occurred at the
measuring point S14, with a settlement value of 3.8 mm. As seen from Fig. 7 (c), the settlement
area did not vary significantly 3 months after the pumping. However, a notably concentrated
settlement occurred on measuring point S21, on the west side of the embankment, with a value
of 4.4 mm, which is the greatest settlement value of the test, again manifesting that the ground
settlement lags the deep pumping. As seen from Fig. 7 (d), the settlement at the measuring point
S21 gradually dissipated and its range expanded. The settlement value decreased to 3.3 mm.

Note that no obvious ground settlement occurred in this test, suggesting that the existence of
multiple aquitards impeded the free transfer between different aquifers. Also, the test results indicate that the permeability of the strata on the west side is greater than that of the east side.

Fig. 6. The variation of surface settlement distribution during the pumping.
(a) Aug. 10, 2018; (b) Aug. 15, 2018.

Fig. 7. The variation of surface settlement distribution after the pumping.
(a) Aug 24, 2018; (b) Sep. 11, 2018; (c) Nov. 17, 2018; (d) Jan. 16, 2019.
4.3. Characterization of the subsurface deformation field

In order to further study the influence of the groundwater barrier on the deformation connectivity of the strata, the subsurface deformation values acquired by DFOS were substituted into the space-time matrix $B$. Note the buried depth of the constant-temperature layer of the test site is from 10 to 230 m; thus, the measurements of the strain field ranging from the ground surface to 10 m underground were excluded owing to the measuring uncertainty induced by the temperature variation in the variable temperature layer. Thus, the submatrices of the constant-temperature layer were extracted to plot the strain field contours during and after the pumping, as shown in Fig. 8. As can be noted from the figure, the strain concentrates within the acquire layers in Fig. 4. Specifically, restricted by the aquiclude of the clayey layer ranging from the buried depth of 150 to 180 m, the greater strain mainly occurs within aquifer CA3 from the buried depth of 180~230 m.

As seen from Fig. 8(a), during the pumping, the strain values within the buried depth of 10~180 m were tiny. Note obvious compressive strain occurred within aquifer CA3, which corresponds to average daily subsidence of approximately 1.61~2.87 mm calculated by Eq. (7).

As seen from Fig. 8(b), after the pumping, the strata strain field, ranging from the buried depth of 10~180 m, varied slightly; while the significant variation of the strata strain field occurred within 180~230 m underground. Although the strata exhibited compressive strain at the immediate end of pumping, tensile strain started occurring in half a month, suggesting the existence of an obvious and rapid stratum rebound and the rebound evolved from top to bottom.

One month after the end of pumping, the rebound extended from the upper part to the entire
aquifer CA3. Four months after the end of pumping, the rebound rate slowed down owing to the gradual recharging of the groundwater. The stratum rebound of aquifer CA3 ranges from 1.89~2.15mm, calculated by Eq. (7).

Fig. 8. Contour plot of the subsurface strain field.

(a) During the pumping; (b) After the pumping.

The stratigraphic strain field is converted to the accumulated subsurface deformation in accordance with Eq. (7). Fig. (9) compares variation trends of both cumulative subsurface deformation of aquifer CA3 and the corresponding surface settlement over time. As seen from the figure, the surface subsided slightly during the pumping. After the pumping, the settlement rate slowed down, and the maximum of settlement is 3.2 mm, occurring on the 44th day, and then rebounded with small fluctuation. Meanwhile, a sharp compressive deformation of aquifer CA3 occurred during the pumping, and the deformation varied linearly with time. The...
deformation value reached the maximum of 18.24 mm on the first day after the end of the pumping, and then a rebound occurred, whose rate slowed down with time. The deformation of CA3 returned to the initial state five months after the end of pumping. Compared with the subsurface deformation of CA3, the surface settlement is smaller and lagged about 1 to 2 months, suggesting the subsidence induced by the deep pumping is gradually transmitted to the surface.

![Ground deformation trends and fitted curves of borehole D1.](image)

5. Discussion

5.1 Analysis of cumulative ground settlement

As seen from Fig. 9, during the pumping state, aquifer CA3 and surface settlement increased linearly over time; during the postpumping stage, the surface settlement continued to increase linearly, but the rate decreased, while aquifer CA3 exhibited a nonlinear rebound trend. Note linear functions are used to fit aquifer CA3 and surface settlement trend during the pumping. The logarithmic function is used to fit the rebound trend of CA3 during the postpumping, and
A piecewise linear function is used to fit the surface subsidence and the rebound trend of the postpumping stage, respectively. Eqs. (8) and (9) are the fitting functions of the deformation trends of CA3 and ground surface, respectively.

\[
d_d(t) = \begin{cases} 
1.37 + 2.40t & t \leq 7 \\
72.39 - 13.69 \ln(t + 42.57) & t > 7
\end{cases}
\]  

(8)

where \(d_d(t)\) (in mm) is the cumulative deformation of aquifer CA3, and \(t\) (in days) is the duration.

Eq. (8) suggests that continuous pumping within the aquifer would induce sharp subsurface deformation. The underground rebound follows a logarithmic trend and the rebound rate slowed down with time.

\[
d_s(t) = \begin{cases} 
1.53 + 0.11t & t \leq 9 \\
2.34 + 0.02t & 9 < t \leq 50 \\
4.84 - 0.03t & t > 50
\end{cases}
\]  

(9)

where \(d_s(t)\) (in mm) is the cumulative settlement of surface, and \(t\) (in days) is the duration.

Eq. (9) shows that the surface will undergo linear settlement over time during the pumping, and will continue to settle at a low rate after the pumping. This stage of settlement lasted as long as 43 days; such comprises the major part of the total settlement. Subsequently, the surface rebounded linearly with time, and the time recovering to the initial state was the same as that of CA3, suggesting the surface settlement after the pumping is closely related to the subsurface deformation.

Note that the surface settlement was divided into two phases, the former was closely associated with the pumping and the latter was closely related to CA3 stratigraphic deformation. The duration of the surface settlement was nearly 50 days, which is about 1/3 of the time required for the surface rebound, and the time required for both aquifer CA3 and surface to
recover to their initial state was about 150 days. When the water source pumping continuously for \( t_p \) days \((t_p > 6)\), the duration of the formation to recover to its initial state is \( t_f \), then according to Eq. (8) satisfies

\[
72.39 - 13.69 \ln[(t_f - t_p + 6) + 42.57] + 2.4(t_p - 6) = 0 \quad (t_p > 6)
\]

(10)

Eq. (10) is derived to obtain the total recover duration of the strata \( t_f \) and the duration of ground surface settlement \( t_s \), namely,

\[
t_f = 3t_s = \exp\left(\frac{57.99 + 2.4t_p}{13.69}\right) - 48.57 + t_p \quad (t_p > 6)
\]

(11)

Substituting into Eq. (9), the maximum surface settlement is

\[
d_s(t_p) = 2.34 + 0.02 \times t_s = 2.02 + 0.02t_p + 1.38 \exp(0.175t_p) \quad (t_p > 6)
\]

(12)

According to Eq. (12), the maximum surface settlement increases approximately exponentially with the duration of the pumping. Once the dewatering lasts for more than 15 days, the ground settlement will reach 21.4 mm, exceeding the safety limit of 20 mm given by the relevant specifications (Gao et al., 2010). Therefore, the limit duration of continuous dewatering should not exceed 15 days.

### 5.2 Analysis of the curvature radius along the metro line

Metro tunnel, as a typical linear distribution structure, is more sensitive to uneven deformation of the ground along the line. From Fig. 6 and Fig. 7, the settlement differences in the site traversed by this metro were more significant than those in other areas. The settlement data from the settlement monitoring points along the metro line (S14, S1, S2, S3, S4, S5, and S6) were selected to draw the trend plot of cumulative surface settlement along the metro line...
with time by the linear interpolation method, as shown in Fig. 10. The settlement was much less than the specification limit of 20 mm (Gao et al., 2010). Also, obvious settlement grooves occurred in both well groups, respectively, in the middle of which the settlement amount attains the minimum. Note excessive relative settlement reduced the subsidence curvature radius.

Fig. 10. Settlement distribution along the metro line.

The curvature radius, at each monitoring point along the metro line, induced by the longitudinal deformation of the tunnel was calculated by the three-point method (Cupec et al., 2009). Statistically, a relatively small curvature radius occurred on three points, including both settlement grooves and their middle point. The variation trends of the curvature at those three points were plotted in Fig. 11. As seen from the figure, the minimum curvature radius along the metro line occurred at settlement groove 2 on September 11, with a radius of $3.89 \times 10^6$ m. Note that is much greater than the $1.5 \times 10^4$ m specified by the specification, indicating that the short-term dewatering activity has less influence on the tunnel. Also, note that the curvature
radius of those key points decreases exponentially with time during the pumping. Once the pumping last more than 15 days, the curvature radius will be less than the standard value. Within the first week after the end of the pumping, the curvature radius rose rapidly and then fluctuated steadily, suggesting the variation of the longitudinal curvature radius of the tunnel is closely related to the dewatering activities along the metro line.

![Curvature radius graph](image)

**Fig. 11.** The minimum curvature radius of typical sections along the metro line.

### 6. CONCLUSIONS

1. The maximum surface settlement, produced by the 6-day pumping test, was about 4.4 mm, which is less than the 20 mm limit required by the metro protection; the minimum curvature radius was $3.89 \times 10^6$ m, which is much greater than the minimum limit of $1.5 \times 10^4$ m for the longitudinal deformation safety as specified in the specification.

2. The fiber optic cable, vertically buried in the constant-temperature layer, can effectively measure the subsurface strain field and be used to deduce the deformation amount of each stratum based on the measurements.
(3) After the end of pumping, a large settlement occurred on the west side of the test site, which is consistent with the distribution pattern of groundwater level, suggesting the overall distribution of settlement is combinedly affected by the formation permeability and groundwater rechargeability.

(4) Influenced by the vertical distribution of aquitards, deep pumping causes the deformation of the aquifers to be much greater than the surface settlement. Note the surface settlement lags behind the settlement of the aquifer by 1 to 2 months; the surface rebound recovery also exhibits a similar delay.

(5) During the pumping, the deformation of the aquifer and ground surface is linearly compressed with time. After the pumping, the ground surface continues to settle linearly at a slower rate for about 50 days, followed by a slow linear rebound; the aquifer is logarithmically rebounded. Both rebounded to the initial state in about 150 days.

(6) During the pumping, the curvature radius of the settlement grooves along the metro line decreased exponentially with time, and started to rise rapidly and maintained steady fluctuations one week after the end of the pumping.

(7) Although the short-term continuous water supply from the groundwater source has negligible adverse effects on the metro tunnel, the stratigraphic deformation fitting equations indicates that the source should not be continuously pumped for more than 15 days.
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Figure 1

The structure of a metal-reinforced single-core cable (MRC).
Figure 2

Location of the test site. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 3

Test layout. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 4

The layout of subsurface deformation monitoring.

Figure 5

Water level variation. (a) Distribution of water level on Aug. 15; (b) Distribution of water level recovery on Aug. 30. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 6

The variation of surface settlement distribution during the pumping. (a) Aug. 10, 2018; (b) Aug. 15, 2018. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
Figure 7

The variation of surface settlement distribution after the pumping. (a) Aug 24, 2018; (b) Sep. 11, 2018; (c) Nov. 17, 2018; (d) Jan. 16, 2019. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.
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