Behaviour of multi-aquifer system during pumping test

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ABSTRACT

This paper presents a case history of behavior during a series of pumping tests in an alternated multi-aquifer-aquitard system in Tianjin, China. The groundwater system at the test site is composed of a phreatic aquifer and three confined aquifers. Three groups of single well pumping tests were conducted in aquifers to obtain the hydrogeological parameters of aquifers and to investigate the hydraulic connection between aquifers. Test results show that there is hydraulic connection between aquifers. Moreover, analytical method is employed to analyze hydrogeological parameters. The analytical solution using Dupuit equation was performed for phreatic aquifer and Hantush-Jacob and Cooper-Jacob method was conducted for confined aquifers.

Keywords: pumping test, hydrogeological parameter, analytical method

1 INTRODUCTION

As a result of expansion of city construction, the exploitation of underground space is drawing more and more attention and excavations of deep foundation pit become increasingly deeper with greater excavation areas. Soft Quaternary deposits in the coastal regions of China are usually alternated multi-aquifer-aquitard system (MAAS) with characteristics of very high groundwater head (Xu et al., 2009, 2012; Shen and Xu, 2011). When excavation pits are located in this kind of soft deposit, dewatering is used to ensure excavation safety. Many historical cases have shown that such an exercise may cause significant ground settlement or even breaking of pipelines, subsiding and/or tilting of buildings (His et al., 1996; Shaqour and Hasan, 2008). In an analysis of excavation dewatering, understanding hydrogeological parameters such as hydraulic conductivity, transmissivity, and storage coefficient, can be very helpful in diminishing settlement caused by dewatering.

In general, there are two ways to understand the hydrogeological parameters of soils: laboratory tests and filed tests. Among them, field tests such as pumping test and slug test are used the most widely. Slug test is mainly used in weak aquifers that are difficult to draw groundwater continuously and pumping test is commonly used in aquifers that can draw groundwater easily. Generally, analytical method for non-steady flow has been used to obtain hydrogeological parameters by matching observed drawdown data (Dupuit, 1863; Theis, 1935; Cooper and Jacob, 1946; Hantush and Jacob, 1955).

This paper presents a field case study of pumping test conducted in Tianjin, China. Analytical method is applied to get hydrogeological parameters.

2 OUTLINE AND GEOLOGIC CONDITION OF THE TEST SITE

The test site was at Tianjin transportation Hub. Tianjin transportation Hub is located in the Hedong district of Tianjin, including traffic square behind the Tianjin Railway Station, landscape square in front of the Tianjin station, and the relative municipal works. Fig. 1 (a) shows the plan view of the pumping test site and Fig. 1(b) presents the plan view of wells.

The test site has the elevation of 2.3 to 2.4 m above the sea level. The studied area is characterized by marine-terrestrial interlaced phase with silty sand, silt and silty clay, see Fig. 2. The first layer is uncontrolled fill (Artificial layer) in the upper 2.6 m below ground surface, followed by silty clay and silt to a depth of 12.6 m. The next layer is sily clay extending to a depth of 20.5 m, underlain by silt and silty sand to a depth of 32.1 m. These are underlain by silty clay with some silt...

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to a depth of 44.4 m. The subjacent layer is silty clay to a depth of 47.2 m. Beneath this layer, there exists a layer of silty clay until the termination depth of 55 m. There are one phreatic aquifer (hereinafter labeled as Aq0) and two confined aquifers (hereinafter labeled as AqI to AqII). The aquifers are separated by three aquitards (hereinafter labeled as AdI to AdIII). The values of $k_s$ and $k_v$ estimated from laboratory tests were obtained from soil test results using the samples oriented in horizontal and vertical directions, respectively (Fig. 2).

3 PUMPING TESTS

It can be seen from Fig. 1(b) that there were 11 wells located at planning square. The pumping wells W1 to W3 were installed in Aq0 to AqII to a depth of 18 m, 35 m, 50 m, respectively. The three wells were fully penetrating wells with an internal radius of 300 mm and an external radius of 400 mm. The screens of wells were 9 m long in Aq0, 11 m long in AqI, and 4 m long in AqII. Fig. 3 presents the curves of drawdown versus time during single-well test. Within each pumping test, the change in groundwater head follows a similar trend. At the beginning of a pumping test, groundwater head declined rapidly, and then gently declined until it reached to a steady level. When the pump shut down, the groundwater head recovered quickly. The maximum drawdown of AqI was 0.125 m and the groundwater level of AqII didn’t change during pumping test in Aq0. The maximum drawdown of Aq0 was 1.1 m and maximum drawdown of AqII was 0.3 m during pumping test in AqI. Although the pumping rate of W3 was only 28.13 m$^3$/d, the groundwater level of AqII declined largely, while groundwater level of AqI did not change.

![Fig. 1 (a) Plan view of pumping test site, (b) Plan view of wells](image-url)

![Fig. 2 Soil profile and properties at the construction site](image-url)
The hydraulic connection between AqI and AqII was shown in Fig. 3, curves of s versus log t. The pumping tests indicate that there is hydraulic connection between Aq0 and AqI, AqI and AqII. However, hydraulic connection between AqI and AqII can’t express only the pumping rate is big enough. That is to say, the hydraulic connection between AqI and AqII is worse than that of AqI and Aq0.

4 ANALYSES OF AQUIFER PARAMETERS

Dupuit equation Hantush-Jacob and Cooper–Jacob method were selected to calculate parameters of Aq0, AqI, and AqII.

4.1 Aq0, Dupuit equation

The Aq0 pumping test was analyzed by using the Dupuit equation (1863).

\[ k = \frac{0.732Q \lg(r_1 / r_2)}{(2H - s_1 - s_2)(s_1 - s_2)} \]  

(1)

where \( H \) is average thickness of Aq0=9.6 m, \( r \) is the distance from monitoring wells to pumping well, \( s \) is drawdown, \( s_1 \)=1.52 m at \( r_1=3.35 \) m and \( s_2=0.97 \) m at \( r_2=7.9 \) m, \( Q \) is constant pumping rate=14.69 m³/d. Substituting into Eq. (1) and solving for \( k \)=0.44 m/d.

4.2 AqI, Hantush-Jacob, s versus log t

The AqI pumping test was analyzed assuming confined aquifer flow with leakage recharge. Fig. 4 shows the fit curve for W2 pumping test at a constant flow rate \( Q=102.96 \) m³/d. According to the method of Hantush-Jacob (1955) for confined aquifers, the transmissivity \( T \), the storativity \( S \), and the leakage factor \( B \) can be calculated by \( s, t, W(U, r/B) \) and \( 1/u \) on or out of the fit curve. The calculated \( T \) values were in the range of 17.91-21.68 m³/d, \( S \) values were in the range of 1.54-20.3×10⁻⁴, and \( B \) values were in the range of 98-178 (Table 1).

4.3 AqII, Cooper–Jacob, s versus log t

For AqII, The semilog graph of Cooper and Jacob (1946) was used here to calculate the hydrogeological parameters. Two detailed graphs of \( s \) versus \( \log t \) are shown in Fig. 5. The transmissivity \( T \) is given by the slope of the linear portion of the graph and the storativity \( S \) is given by the time intercept. The calculated \( T \) values ranged from 2.14 to 3.22 m³/d, and \( S \) values ranged from \( 9.11 \times 10^{-3} \) to \( 3.69 \times 10^{-4} \) (Table 1).

The hydraulic conductivity \( k \) was computed by dividing the \( T \) value for AqI and AqII by the thickness of each sand stratum. All values for hydrogeological parameters are listed in Table 1.

5 SUMMARY

1) Pumping tests indicate that there is hydraulic connection between Aq0 and AqI, AqI and AqII and the hydraulic connection between AqII and AqI is poorer than that between Aq0 and AqI. Thus, the leakage effect of the aquitards plays an important role in the variation of the groundwater level of aquifers during pumping tests.
2) The value of hydraulic conductivity of Aq0 is calculated using Dupuit equation and the values of hydraulic conductivity, transmissivity and storage coefficient and of the AqI and AqII are estimated using Hantush-Jacob and Cooper–Jacob method respectively. The hydraulic conductivity of Aq0 is 0.44 m/d. The average values of hydraulic conductivity, transmissivity and storage coefficient of AqI are 3.99 m/d, 19.90 m²/d and 8.72×10⁻², respectively, and of AqII are 1.30 m/d, 2.61 m²/d and 1.99×10⁻², respectively.

3) To diminish settlement caused by dewatering, leakage effect of aquitards should be considered in foundation pit dewatering design.

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**Table 1. Hydrogeological parameters from pumping tests.**

| Aquifer | Method              | Monitoring well | r (m) | T (m³/d) | S (m²/d) | k (m/d) | B (Adl) | Average T (m³/d) | Average S (m²/d) | Average k (m/d) |
|---------|---------------------|-----------------|-------|----------|----------|---------|---------|-----------------|-----------------|-----------------|
| Aq0     | Dupuit equation     | P1-1            | 3.35  | /        | /        | 0.44    | /       | /               | /               | 0.44            |
|         |                     | P1-2            | 7.90  | /        | /        | 0.44    | /       | /               | /               | /               |
| AqI     | Hantush-Jacob       | P2-1            | 3.85  | 21.68    | 4.32E-4  | 4.34    | 127     | 19.90           | 8.72E-4         | 3.98            |
|         |                     | P2-2            | 8.95  | 20.10    | 2.03E-3  | 4.02    | 178     |                 |                 |                 |
|         |                     | P2-3            | 19.75 | 17.91    | 1.54E-4  | 3.58    | 98      |                 |                 |                 |
| AqII    | Cooper-Jacob        | P3-1            | 4.00  | 2.14     | 1.36E-4  | 1.07    | /       | 2.61            | 1.99E-4         | 1.30            |
|         |                     | P3-2            | 9.10  | 3.22     | 9.11E-5  | 1.61    | /       |                 |                 |                 |
|         |                     | P3-3            | 19.90 | 2.46     | 3.69E-4  | 1.23    | /       |                 |                 |                 |

Note: r = distance from monitoring well to pumping well; T = Transmissivity; S = Storage coefficient; k= hydraulic conductivity, B= leakage factor.