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Semi-analytical solution to pumping test data with barrier, wellbore storage, and partial penetration effects

Yong-Xia Wu[a,b,c], Jack Shuilong Shen[a,b,c,*], Wen-Chieh Cheng[a,b,c,*], Takenori Hino[d,e]

[a] State Key Laboratory of Ocean Engineering, Shanghai 200240, China
[b] Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration (CISSE), Shanghai 200240, China
[c] School of Naval Architecture, Ocean, and Civil Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Minhang District, Shanghai 200240, China
[d] Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[e] Institute of Lowland and Marine Research, Saga University, Japan

A R T I C L E I N F O

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A B S T R A C T

There exist some difficulties in determining aquifer parameters based on pumping test data within a partially penetrated retaining walls using traditional Cooper-Jacob method. Many other site-specific factors, such as the effect of partially penetrating well and the large diameter of the wells, cannot easily be accommodated in theoretical well formulae. The semi-log drawdown-time curves affected by the effects of barrier, wellbore storage, and partial penetration well can be characterised by four distinct stages of drawdown: i) Stage I, drawdown is unaffected by the barrier, ii) Stage II, drawdown is significantly influenced by the barrier, iii) Stage III, the drawdown-time curve runs parallel to that deduced from greenfield conditions, and iv) Stage IV, the drawdown becomes a constant value. To handle the four distinct stages of drawdown, a semi-analytical method using the slope of the late-time drawdown asymptote of Stage III for determining the transmissivity is proposed. The horizontal intercept, resulting from an extension of the late-time drawdown asymptote from Stage II, is used for determining the storage coefficient. Pumping test data from a case history are analysed using the proposed semi-analytical method, and the results obtained are compared with those deduced from the numerical simulation. The comparison between the analytical results and those obtained from the numerical simulation appeared satisfactory.

1. Introduction

The Quaternary deposit in coastal regions of China composed of clay, silt, sand, and gravel can be characterised by an alternating multi-aquifer system (MAS) (Wang et al., 2009; Shen et al., 2014; Xu et al., 2016). In some cases, the piezometric pressure in confined aquifers could be higher than the ground surface level. To control the buoyancy force throughout a deep excavation and allow dry construction, groundwater withdrawal is essential for project success. During deep excavation, retaining structures such as diaphragm walls, jet grouted columns, and deep-mixing piles (Du et al., 2015; Tan and Wang, 2015a, 2015b; Shen et al., 2013b, 2017) have been utilised to prevent groundwater from seeping into the excavation pit. Since excessive groundwater withdrawal may cause ground surface settlement and building tilting (Roy and Robinson, 2009; Pujades et al., 2014a), it is not only a geotechnical engineering problem, but also a surrounding environmental issue. As the water flows into the well, the water levels, or piezometric pressures, in the aquifer around the well decrease, and this decrease gradually diminishes with increasing radial distance from the well, thereby resulting in a depressioncone (Shen and Xu, 2011; Pujades et al., 2014b; Xu et al., 2014; Wu et al., 2015). this decrease diminishes with distance from the well, thereby resulting in a conical depression (Shen and Xu, 2011; Pujades et al., 2014b; Xu et al., 2014; Wu et al., 2015). For instance, in Shanghai the depression cone of the shallowest confined aquifer has formed in the city centre. Similar cases have also been found in Tianjin and Ningbo (Shen et al., 2015a; Xu et al., 2014). The piezometric level in Shanghai city centre is within a depth range of 3 to 4 m below the ground surface, while the local piezometric level could reach 1 m above the surface. Thus, groundwater withdrawal during deep excavation has attracted particular attention. In the design phase, the aquifer parameters, e.g., hydraulic conductivity (k), transmissivity (T), and storage coefficient (S), are required for the purpose of environmental protection.

Generally, a pumping test is used to investigate the drawdown characteristics for determining the aquifer parameters before bulk excavation, however, underground structures are densely distributed

* Corresponding authors.
E-mail addresses: wxia2011@sjtu.edu.cn (Y.-X. Wu), slshen@sjtu.edu.cn (J.S. Shen), s2428030@gmail.com (W.-C. Cheng), hino@ilt.saga-u.ac.jp (T. Hino).

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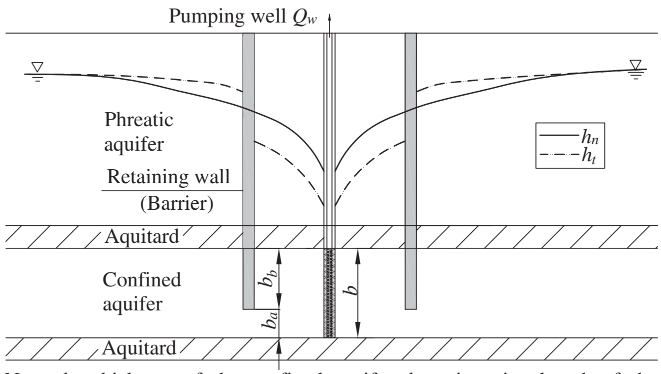

Note: b = thickness of the confined aquifer; b_b = insertion length of the barrier into confined aquifer; b_a = width of the opening; h_n = confined water head without barrier; h_t = confined water head with barrier.

Fig. 1. Relative position of barrier in the confined aquifer.

in response to rapid urbanisation and they may have significant implications on the drawdown characteristics throughout pumping tests in urban areas (Ding et al., 2008; Pujades et al., 2012; Ma et al., 2014; Font-Capo et al., 2015; Attard et al., 2016). Since the thickness of aquifer is usually unknown, any underground structures are regarded as being partially penetrated. The development of the depression cone become discontinuous, as depicted in Fig. 1. This means that the groundwater drawdown from inside the excavation pit is greater than that from outside the pit because of the barrier effect resulting from the presence of the diaphragm wall. In this case, theoretical well formulae such as the Theis equation (Theis, 1935) and the Cooper and Jacob equation (Cooper and Jacob, 1946) cannot be used. Apart from this problem, there are many other site-specific factors, such as the effects of partial penetration well and water storage, involved in the estimation of aquifer parameters and their implication also has to be taken into account.

At present, back-calculation based upon the results of a numerical simulation has become popular, particularly for handling the groundwater drawdown from pumping tests involving a partial penetration well and barrier effects (Luo et al., 2008; Wang et al., 2012, 2013). Additionally, it can be used for not only investigating the anisotropic nature of a stratum, but for estimating horizontal and vertical hydraulic conductivities; however, the establishment of a numerical model is not an easy task and the selection of input parameters will determine the correctness of the back-calculation. The objectives of this study are i) to develop a simple drawdown data reduction method based upon pumping test results with an arbitrarily shaped barrier, wellbore storage, and partial penetration well effects and ii) to establish a numerical model not only giving a prediction of aquifer parameters comparable with those derived from the proposed semi-analytical method, but capturing complex groundwater flow phenomena and the anisotropic nature of the ground.

2. Cooper-Jacob method for an infinite confined aquifer

The basic assumptions for the Theis method (Theis, 1935) include: "(i) the confined aquifer is homogeneous, isotropic, and of uniform thickness over the area affected by pumping, (ii) the well diameter is small and the wellbore storage effect can be negligible, (iii) the pumping well is fully penetrating well, and (iv) there is no leakage from the overlying/underlying formation or groundwater recharge from the possible hydrogeologic boundary" (Ni et al., 2011; Shen et al., 2015b). Cooper and Jacob found that the second- and higher-order terms in the Theis well function may be neglected when the argument, u, of the well function is small (Cooper and Jacob, 1946).

The coefficient of transmissivity, T, can be derived through the slope, i_s, of the linear section of Theis's curve (1935) using the straight line approximation proposed by Cooper and Jacob (1946):

$$T = \frac{2.30Q}{4\pi i_s} \tag{1}$$

and the storage coefficient, S, is obtained by using the horizontal intercept, t_0, of an extension of the late-time drawdown asymptote resulting from a typical drawdown curve:

$$S = \frac{2.25Tt_0}{r^2} \tag{2}$$

where r is the distance between observation well and pumping well. When the values of i_s, t_0, and r are known, T and S can be calculated by using Eqs. (1) and (2), respectively. The hydraulic conductivity, k, can then be obtained using Eq. (3).

$$k = \frac{T}{b} \tag{3}$$

where b is the thickness of the confined aquifer.

3. Factors affecting the drawdown curve

The groundwater level in an aquifer can be affected by periodic loading (Ni et al., 2011, 2013). Since complex groundwater level fluctuations are caused not only by tidal effects, but by atmospheric pressure, precipitation, groundwater withdrawal, and local topography, the use of sinusoidal functions to remove the tidal constituents from pumping test data is inapplicable (Liu, 1996; Ni et al., 2011, 2013). Additionally, many other site-specific influencing factors such as the large diameter of the wells and the partial penetration well effect must also be taken into account. It can be observed from Fig. 2 that the wellbore storage effect and the partial penetration well effect can significantly affect the early-time and late-time drawdowns, respectively, of a typical drawdown curve. The two influencing factors are discussed below, and the barrier effect will be studied thereafter.

3.1. Wellbore storage effect

When pumping is conducted in a large-diameter well, the groundwater is not coming from the surrounding aquifer but from the water originally stored in the well casing (Chapuis and Chenaf, 2003; Ni et al., 2011; Sethi, 2011). Since the adjacent observation well requires a finite time to respond to a pumping-induced piezometric pressure decline in aquifer, this implies that there is a time delay before the response in the form of groundwater drawdown in the observation well. It is also worth noting that, during pumping in a confined aquifer, the drawdown in an

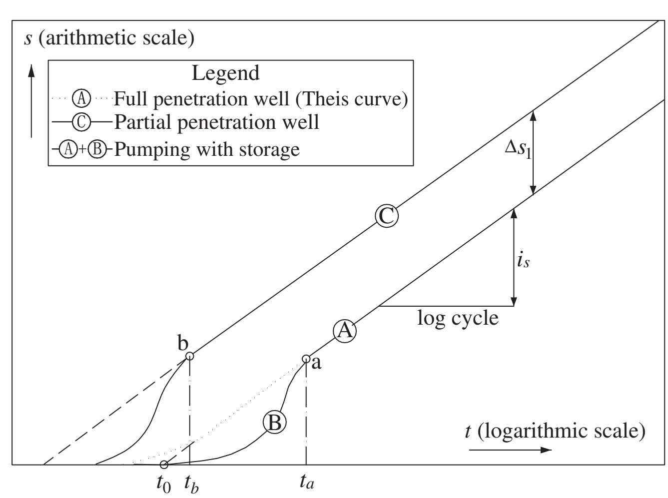

Fig. 2. Schematic illustration of drawdown-time curve with wellbore storage and partial penetration well effects.