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Characteristics of dewatering induced drawdown curve under blocking effect of retaining wall in aquifer

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SUMMARY

For deep excavation pits that require the pumping of confined groundwater, a combination of a retaining wall and dewatering with large-diameter wells is usually adopted during excavation to improve safety. Since a retaining wall has a much lower hydraulic conductivity than the surrounding material in the aquifer, blocking of seepage to prolong the seepage path of the groundwater outside of the pit is effective. The retaining walls used during excavation dewatering cause hydraulic head drawdown inside the pit much faster than outside the pit. Thus, difference in hydraulic head between inside and outside of the pit increases. To investigate the mechanism of the blocking effect, numerical simulation using the finite difference method (FDM) was conducted to analyze the effects of pumping in the pit. The FDM results show that drawdown varies along the depth of the confined aquifer. The influence factors of drawdown inside and outside the pit include insertion depth of retaining walls, anisotropy of a confined aquifer and screen length of pumping wells. In addition, FDM results also show that the drawdown-time curve can be divided into four stages: in Stage I, drawdown inside the pit is very small and outside the pit it is almost zero; in Stage II, drawdown increases quickly with time; in Stage III, the drawdown curve is parallel to the Cooper–Jacob curve on semi-log axes; and in Stage IV, the drawdown becomes constant. These characteristics of the drawdown curve under the blocking effect of a retaining wall in an aquifer provide a way of estimating hydrogeological parameters according to pumping test results.

1. Introduction

According to statistics, the resident population accounts for an increasing proportion of the total population, rising from 8.6% in 1985 to 19.7% in 2010 in coastal regions of China (Fu et al., 2014). The growth of the urban populations in cities were caused a series of problems, such as traffic congestions, land shortages and a reduction in available green spaces. To counter these problems, large-scale underground structures are increasingly being constructed in urban areas, using deep excavation techniques (Jiao et al., 2008; Peng et al., 2011; Ng et al., 2012; Tan et al., 2015a,b; Tan and Wang, 2015a,b). Generally, Quaternary deposits composed of gravel, sand, silt, or clay are extensively distributed in the coastal region. These soft deposits were sedimented under marine or deltaic environments during palaeoclimatic conditions forming a multi-aquifer-aquitard system (MAAS) (Xu et al., 2013a, 2015; Du et al., 2014; Wu et al., 2014, 2015a,b). The MAAS primarily consists of a phreatic aquifer and several aquifers that are separated by aquitards. The characteristics of the sediments include a very high compressibility and low permeability of aquitards and high groundwater levels in both phreatic, and confined, aquifers (Yin et al., 2011, 2016; Wang and Jiao, 2012; Fan et al., 2013, 2014; Shen et al., 2014, 2015a,b; Ye et al., 2015).

Since the start of the 21st century, more excavations have been reached to the depths of 20–30 m, or even up to 40 m (Luo et al., 2008; Xu et al., 2012a). For these deep excavations, not only the groundwater in the phreatic aquifer should be drained but also the head of water in the confined aquifer should be lowered. Under such conditions, retaining walls, for example, constructed using deep mixing columns, jet grouting columns, and diaphragm walls, are all used to retain the surrounding soils and to prevent groundwater from flowing into the pits (Shen et al., 2008, 2013b; Pujades et al., 2012a,b; Wang et al., 2013, 2014; Wu et al., 2015d,e). In addition, coastal region aquifers are also easily influenced by sea water intrusion to induce salinisation of fresh groundwater due to sea level rise and consequent deterioration

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of the ecosystem (Werner and Simmons, 2009; Pool and Carrera, 2010). Thus, hydraulic barriers (i.e., diaphragm walls, soil–bentonite vertical cutoff walls, soil–cement–bentonite vertical cutoff walls) can also be applied to prevent transport of contaminants in an aquifer as well as to prevent seawater intrusion (Anderson and Mesa, 2006; Luyun et al., 2011). In groundwater remediation projects, these vertical hydraulic barriers are also used extensively to control the migration of contaminants in groundwater so that contaminated groundwater can be treated by in situ remedial technologies (Sharma and Reddy, 2004; Malusis et al., 2009; Du et al., 2015a,b, 2016). For example, Du et al. (2015a,b) proposed a new type of soil-bentonite vertical cutoff wall comprising a clayey soil and calcium bentonite materials for containing contaminants in the groundwater. The crucial factors affecting the permeability of the cutoff wall were investigated by Du et al. (2015a,b). Using the empirical formula proposed by Du et al. (2015a,b), the permeability of the soil-bentonite vertical cutoff wall can be predicted with satisfactory accuracy.

In practice, when the retaining wall cuts off the aquifer completely, dewatering in the excavation pit just lowers the groundwater level inside the pit and it cannot induce drawdown outside the pit under the conditions in which the quality of the retaining wall is perfect (i.e. it is impermeable). For most excavations, since the thickness of the aquifer is high, the retaining wall only partially cuts off the confined aquifer. When pumping is conducted within the pit, groundwater inside the pit flows into the well screen at the right angles, but the direction of seepage of the groundwater outside the excavation pit changes from the horizontal to the vertical, due to the existence of the retaining walls. Therefore, the retaining walls lengthen the seepage path for groundwater flowing from outside the excavation pit into the well. Moreover, groundwater outside the pit can only flow into the excavation pit from the opening between the retaining walls and the bottom of the aquifer. As a result, the existence of the retaining walls changes the seepage direction, extends the seepage path, and reduces the seepage area in excavation dewatering projects (Butler and Liu, 1991; Jiao et al., 2006, 2008; Vilarrasa et al., 2011; Xu et al., 2014). In excavations, long-term dewatering is conducted and groundwater levels within and outside the excavation pit should be recognized to ensure excavation safety. Thus, it makes a sense to study the stable groundwater level distribution.

In general, a pumping test is carried out to obtain the hydrogeological parameters of an aquifer before installing retaining walls there to support any excavation project. However, in congested urban centres, such as Shanghai, since there are already many pre-existing underground structures nearby, it is difficult to do pumping tests within an underground structure-free region (for the density of underground structures, refer to Xu et al., 2012b, 2014). In other cases, to protect the environment and/or due to limitations of site conditions, pumping tests cannot be conducted before wall construction. Several wells are installed in the excavation pit after the construction of wall, and a pumping test is then conducted to obtain sufficient parameters so that the dewatering system can be optimised. The existence of retaining walls exerts an influence on the behaviour of the groundwater seepage and this makes the thickness of the aquifer discontinuous and any changes therein, staged. In these conditions the hydrogeological parameters cannot be back-calculated using existing analytical methods based on the data from pumping tests, e.g. using the Theis method (1935), Cooper and Jacob method (1946), or Hantush method (1960). Therefore, it is meaningful to investigate groundwater level variations to estimate the hydrogeological parameters based on the pumping test results with walls.

In the present time, research into the blocking effect of retaining walls focuses on the numerical method used to predict the drawdown and ground settlement caused by dewatering (Ervin and Morgan, 2011; Wang et al., 2009; Xu et al., 2008, 2013b; Pujades et al., 2014a,b). There is a few research on the mechanism of the blocking effect (Vilarrasa et al., 2011; Pujades et al., 2012b). Vilarrasa et al. (2011), Pujades et al. (2012b) analysed drawdown variation under different permeability of the retaining walls during dewatering in a closed circular and linear excavation, respectively. Their findings cannot represent partially penetrated retaining walls. The objectives of this study are as follows: (*i*) to understand the distribution of drawdown along the longitudinal depth of a confined aquifer, and (*ii*) to study the variation of drawdown over time during dewatering with a barrier.

2. Problem set-up

In general, the seepage follows a simple pattern when pumping groundwater in a foundation pit with an annular barrier. Thus the circular barrier is adopted in this paper to study the blocking effect of retaining walls. Fig. 1 shows a sketch of the problem. As it is evident in Fig. 1(a), r_0 is the inner radius of the pit, and L_b is the thickness of the retaining wall (which acts as barrier). A pumping well is in the centre to lower the groundwater head in the confined aquifer, with a pumping rate of Q_w. Fig. 1(b) shows a sectional view of the circular pit and the relative position of the retaining wall in the confined aquifer. Here, b is the thickness of the confined aquifer, b_b is the insertion depth of the retaining wall into the confined aquifer, b_a is the distance from bottom of the retaining wall to the bottom of confined aquifer, and b_e is the distance from top of the confined aquifer downwards to an arbitrary point.

3. Numerical simulation of drawdown due to presence of barrier

3.1. Numerical model

Based on Darcy's law and the principle of continuity, the governing equation for groundwater seepage in saturated media is expressed as follows (Bear, 1979; Shen and Xu, 2011; Wang et al., 2012):

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) - Q = S_S\frac{\partial h}{\partial t} \tag{1}$$

where k_{ij} = hydraulic conductivity; h = hydraulic head; Q = external source/sink flux; S_s = specific storage; t = time.

The initial condition is expressed as:

$$h(x,y,z,t)|_{t=t_0} = h_0(x,y,z) \tag{2}$$

where $h_0(x, y, z)$ = initial hydraulic head at point (x, y, z).

The boundary conditions are expressed as:

$$h(x,y,z,t)|_{\Gamma_1} = h_1(x,y,z,t) \tag{3}$$

$$\left.\left(k_{xx}\frac{\partial h}{\partial n_x} + k_{yy}\frac{\partial h}{\partial n_y} + k_{zz}\frac{\partial h}{\partial n_z}\right)\right|_{\Gamma_2} = q(x,y,z,t) \tag{4}$$

where $h_1(x, y, z, t)$ = constant head on boundary Γ_1; n_x, n_y, and n_z = unit normal vector on boundary Γ_2 along x, y and z directions; $q(x, y, z, t)$ = lateral recharge per unit area on boundary Γ_2; Γ_1 = first type of boundary condition; Γ_2 = second type of boundary condition.

3.2. Model background description

Based on the circular pit described in the previous section, a numerical model is adopted to investigate the characteristics of the drawdown curve under the influence of a barrier during excavation dewatering. This study is based on typical layered