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Slug Test Analysis in Vertical Cutoff Walls with Consideration of Filter Cake

연직차수벽에서 필터케익을 고려한 순간 변위시험 해석방법

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SYNOPSIS: In constructing a slurry trench cutoff wall, a thin but relatively impermeable layer called filter cake can be formed on the excavation surface. The filter cake significantly influences the result of slug test analysis in the cutoff wall. This study is to examine the effect of filter cake on evaluating in situ hydraulic conductivity of the vertical cutoff wall along with slug test analyses. The numerical program Slug_3D was modified to take filter cake into account in the slug test simulation. With consideration of filter cake, the type curve method and the modified line-fitting method were used to reanalyze the case study taken from a landfill site. The previous results achieved by Choi and Daniel (2006b) without consideration of filter cake have been compared with the results in this study. The considerable difference between the two results shows the necessity of considering the filter cake in practice.

Key words: slug test, slurry, cutoff wall, filter cake, hydraulic conductivity, type curve method, line-fitting method.

1. Introduction

The slug test is usually used to evaluate hydraulic conductivity of aquifers and aquitards (Hyder et al. 1994, Butler 1998). There are four analytic and semi-analytic methods for analyzing the results of a slug test: (1) The Hvorslev (1951) method; (2) the Cooper et al. method (Cooper et al. 1967, Papadopulos et al. 1973); (3) the Bouwer and Rice method (Bouwer and Rice 1976, Bouwer 1989); and (4) the Kansas Geological Survey (KGS) method (Hyder et al. 1994). The line-fitting methods such as the Hvorslev method and the Bouwer and Rice method have a disadvantage not considering compressibility of a soil mass. The type curve methods including the Cooper et al. method and the KGS method take into account the compressibility.

The hydraulic conductivity of vertical cutoff walls can also be estimated by the slug test using a single well set up in the wall (Yang et al. 1993, Britton et al. 2002, Choi and Daniel 2006a,b). However, all the conventional methods cannot be directly used for analyzing a slug test result in a vertical cutoff wall because they do not account for the boundaries of the wall, which can be located close to the well intake section, or they do not consider the compressibility of the backfill material. In addition, the screen will not be centered in the wall if the centerline of the wall is not located in the field exactly, if the wall is not vertical, or if the borehole is not vertical (EMCON 1995, Daniel and Choi 1999, Choi and Daniel 2006a,b).

Some improvements were made to empower the methods for cases of cutoff walls. Britton et al. (2002) derived shape factors, which are used for interpreting the slug test results in vertical cutoff walls. However, the method proposed by Britton et al. (2002) is also based on the assumption that the soil-bentonite backfill is incompressible. Recently, Choi and Daniel (2006a,b) proposed a new set of type curves for the type curve method and engineering charts of reduction factor, f, of cutoff walls, and of $\ln(R_e'/r_w)$ of aquifers for the modified line-fitting method to analyze the results of slug test in vertical cutoff walls. In this work, the Chirlin's (1989) suggestion was adopted to introduce a modified effective radius, R_e', for compressible aquifer. The type curves and engineering charts were developed using the numerical program Slug_3D (Choi 2007). This program can simulate the slug test in the vertical cutoff wall with consideration of compressible materials, of boundaries between the vertical cutoff wall and the surrounding formation, and of variable hydraulic properties with a change of effective stress (Choi 2007).

Nevertheless, the filter cake has not been considered in slug test analyses in vertical cutoff walls. Because the filter cake has a very low hydraulic conductivity and exists between the cutoff wall and the natural soil formation, it directly influences the boundary conditions of the wall. Therefore, the role of filter cake in slug test analyses to evaluate hydraulic conductivity of a cutoff wall need to be considered necessarily.

In this paper, the authors examined the effect of filter cake on the slug test result in vertical cutoff walls with the aid of the program Slug_3D. Based on the study on the effect of filter cake, the boundary conditions of the model of cutoff wall were modified to the no-flux condition to consider the filter cake in the analysis. The methods proposed by Choi and Daniel (2006a,b) were also modified and utilized to reanalyze the case study that has been performed by Choi and Daniel (2006a) for vertical cutoff walls at the West Contra Costa Sanitary Landfill in Richmond, California. A discussion on the comparison between the previous and current results highlights the importance of considering filter cake in practice.

2. Existence of filter cake in cutoff wall construction

There are two steps in constructing a cutoff wall: (1) trench excavation, and (2) backfilling. In the first step, a trench is excavated to the designed depth and filled with a bentonite-water slurry to maintain trench stability. Because of a higher fluid pressure inside the trench, which must be retained throughout the first step of construction, the slurry tends to permeate the walls of the trench. Consequently, a filter cake can be formed on the excavation surface and may remains intact even after the second step is finished. Two mechanisms of filter cake formation depend on the gradation of the adjacent natural soil formation and the gradation of slurry if the slurry contains suspended soil particles. More detailed information on filter cake formation is referred to Filz et al. (1997).

In addition, Filz et al. (1997) found that if the D_{15} size of the natural soil is less than 0.4 mm, a bentonite filter cake will possibly form on the face of an excavation supported by pure 6% bentonite-water slurry. For the case of slurries that contain suspended soil particles, Henry et al. (1998) found that increasing the unit weight of bentonite-water slurry by the suspension of silt and fine sand increased the critical D_{15} size that allows formation of a filter cake from 0.4 mm for pure 6% bentonite-water slurry to about 9 times the d_{85} size of the slurries. More information about laboratory tests to establish filter criteria for bentonite-water slurries can be found in Filz et al. (1997) and Henry et al. (1998). They suggest that the D_{15} size of the native soil and the d_{85} size of slurry, if the slurry contains suspended soil particles, should be tested to determine whether the filter cake should be considered or not in a slug test analysis.

In cases of existence of the filter cake, its characteristics influence the performance of the cutoff wall. The hydraulic conductivity of filter cake may have an important effect on the behavior of cutoff wall in controlling lateral spreading of ground water. With a range of hydraulic conductivity from 3×10^{-11} m/s to 2×10^{-10} m/s (Henry et al. 1998), filter cake is supposed to be a relatively impermeable membrane altering the characteristic of the boundary of a cutoff wall unexpectedly. The thickness of filter cake was observed less than 0.3 cm (D'Appolonia, 1980). Britton (2001) made a comparison of the measured thickness of actual filter cake and the calculated thickness of filter cake by using Nash's (1974) formula. A representative thickness of 0.5 cm was used for interpretation of the in situ hydraulic conductivity test results by Britton (2001). The following section will describe the effect of filter cake on slurry trench cutoff walls with the aid of program Slug_3D.

3. Effect of filter cake on slug test performed in cutoff wall

Because the filter cake is relatively impermeable and its location is on the interface between the cutoff wall and the natural soil formation, it is of interest to compare the analysis results with consideration of the filter cake to the models with various boundary conditions. In application of Slug_3D for the comparison, the hydraulic conductivity of a cutoff wall was assumed as $k = 1\times10^{-9}$ m/s, and it is assumed that both the cutoff wall and the filter cake has the same value of specific storage that is $S_s = 4\times10^{-5}$ m^{-1}. The thickness of filter cake used in the numerical analyses is 0.6 cm, slightly greater than a common thickness of filter cake, which is observed less than 0.3 cm (D'Appolonia 1980) or about 0.5 cm (Britton 2001). Figure 1 illustrates a plan view and a vertical cross section of a rising-head slug test configuration in vertical cutoff wall with the presence of filter cake layers. The cutoff wall is assumed to be keyed into an aquitard, which is a less permeable layer. The width and depth of the cutoff wall are denoted as W and L, respectively. L_t indicates the distance from the water table to the top of the well intake section. L_w stands for the length of filter pack by assuming no resistance to flow through the filter pack to the well screen because the filter pack is usually more permeable than the formation being tested (Butler 1996). The outside radius of the filter pack and the inside radius of the well casing are denoted as r_w and r_c, respectively. Deviation of the well from the center of the cutoff wall to the center of an eccentric well is denoted as D_v, or nondimensionally as $2D_v/(W–2r_w)$ in program Slug_3D (Choi 2007). The value of s represents the relative vertical position of the well intake section in a vertical cutoff wall and ranges from zero to infinity. If s is unity, the well intake section is at the mid-depth of the wall. Slug_3D is a fully three-dimensional model with a symmetric condition considered in the y-direction. Figure 1 also shows the location of the filter cakes in a geometric configuration of a slug test in vertical cutoff wall and the thickness of the filter cake is scaled up for easy observing.

In this study, the typical geometry of a slug test system in the cutoff wall is selected as r_w = 0.1 m, r_c = 0.02 m, W = 0.8 m, L_w = 1.0 m, L = 11.0 m, s = 1, and D_v = 0. Therefore, the ratio of W/r_w is 8 and the dimensionless compressibility parameter α_p (= $S_sL_wr_w^2 / r_c^2$) is 0.001.

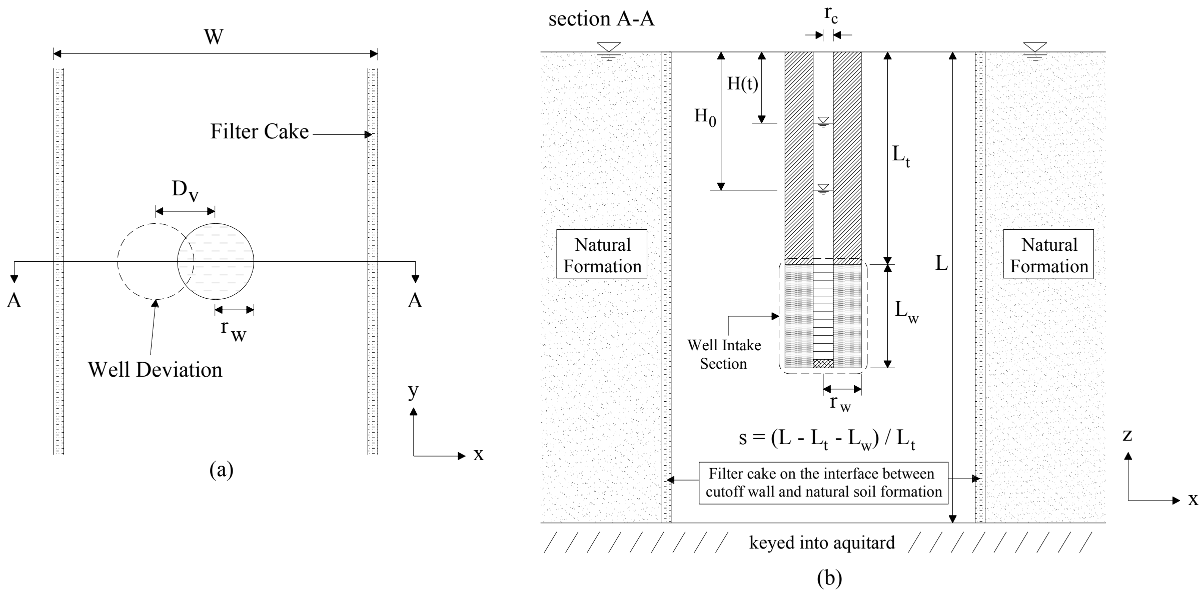

Fig. 1. Slug test configuration in vertical cutoff wall:
(a) Plan view and (b) vertical cross section A-A and the locations of filter cakes

Figure 2 shows that the response data curves have a tendency getting close to the no-flux-boundary response data with an increase in the hydraulic conductivity ratio ($k_{\text{wall}} / k_{\text{cake}}$). The case of $k_{\text{wall}} / k_{\text{cake}}$ = 1,000 becomes close to the no flux boundary condition. Accordingly, if a relatively impermeable filter cake forms on the interface, the no-flux boundary condition should be a better alternative to represent a cutoff wall boundary condition in slug test analyses. The program Slug_3D is modified to employ the no-flux boundary condition on the interface between the vertical cutoff wall and the natural soil formation.

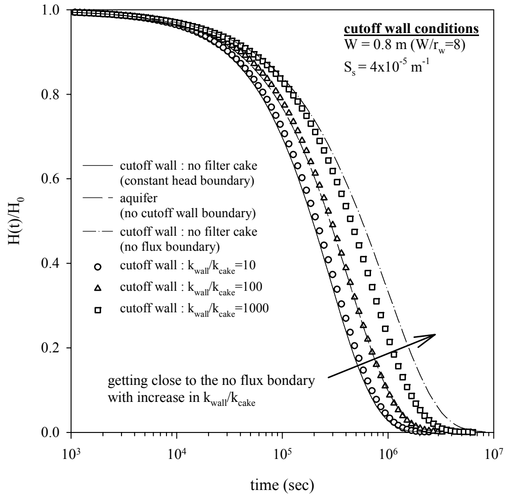

Fig. 2. Filter cake effect on various interface boundary conditions in cutoff walls

4. Evaluation of hydraulic conductivity with consideration of filter cake

4.1 Type Curve Method

A set of type curves is proposed by plotting normalized head recovery versus logarithm of dimensionless time parameter, β_p ($= kL_wt / r_c^2$), for vertical cutoff walls with the presence of filter cake using the modified numerical program Slug_3D. By matching field head recovery data to the type curves, the hydraulic conductivity (k) and specific storage (S_s) for a backfill material in a cutoff wall can be evaluated. Examples of type curves presented in Figures 3 show the normalized head recovery in a range of W/r_w and the nondimensional well eccentricity corresponding to common field conditions. A total of 120 type curves were made and ready to use in practice (Nguyen 2007). In developing the type curves, hydraulic conductivity (k) and specific storage (S_s) were assumed constant in running Slug_3D. Each type curve corresponds to a different value of dimensionless compressibility parameter α_p. The dimensionless parameters α_p and β_p are mathematically verified in the semianalytical solution for a partially penetrating well in an aquifer (Hyder et al. 1994, Butler 1998). The type curves in Figures 3 cover α_p ranging from 1.0×10^{-3} to 1.0, which is a reasonable value of the compressibility of backfill materials.

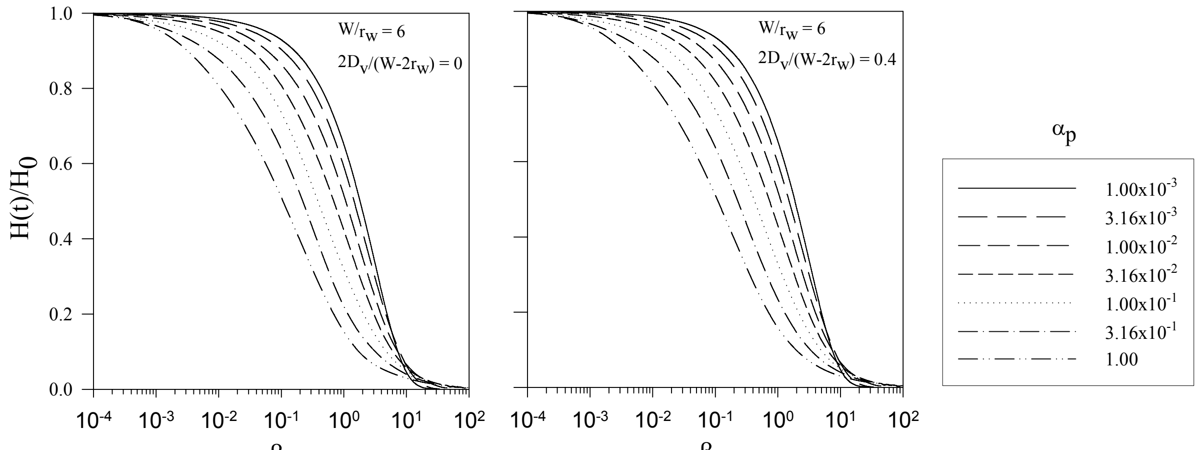

Fig. 3. Type curves for slug test in vertical cutoff walls with consideration of the filter cake - Case $L_w/r_w = 10$ ($L/L_w = 11$ and $s = 1$)

4.2 Modified Line-Fitting Method

The modified line-fitting method was also used as another option for estimating the hydraulic conductivity of a vertical cutoff wall. For the case of no filter cake on the interface between the cutoff wall and the soil formation, Choi and Daniel (2006a) developed a procedure to estimate the hydraulic conductivity of cutoff walls through a slug test analysis by introducing a reduction factor, f. The reduction factor, f, is equal to the ratio of $\ln(R_e'/r_w)_{\text{cutoff wall}}$ to $\ln(R_e'/r_w)_{\text{aquifer}}$. The value of $\ln(R_e'/r_w)$ is defined equal to $2\beta_{p\_0.37}$ ($\beta_p = kL_w t/r_c^2$). The dimensionless time parameter $\beta_{p\_0.37}$ is in correspondence with $H(t)/H_0 = 0.37$. The values of $\ln(R_e'/r_w)$ for the aquifer cases are proposed in Figure 4.

In this study, a modification was made for applying the modified line-fitting method to the cases of the existence of filter cakes. The modification factor, f^*, is introduced to consider the cutoff wall boundary as a no-flux boundary condition. In this case, the no-flux boundary, which is close to the well intake section, reduces the speed of head recovery, so the time for recovery is longer compared to the case of infinite-boundary aquifer. This leads to the greater value of $\beta_{p\_0.37}$ of the cutoff wall case compared to that value of the aquifer case. Hence, for the sake of easy illustration, the modification factor, f^*, is defined as the ratio of $\ln(R_e'/r_w)_{\text{aquifer}}$ to $\ln(R_e'/r_w)_{\text{cutoff wall}}$, which is always less than or equal to unity. Because of slower head recovery caused by no-flux boundaries in the vertical cutoff wall, the value of $\ln(R_e'/r_w)$ has to be modified by f^* in calculating hydraulic conductivity of the cutoff wall as expressed in Equation (1).

$$k = \frac{r_c^2\left[\ln\left(\frac{R_e'}{r_w}\right)/f^*\right]}{2L_w}\frac{1}{t_{0.37}} \quad (1)$$

Some typical modification factors are plotted in Figure 5 for the case of $2D_v/(W-2r_w) = 0$ and $L_w/r_w = 10$. Like the type curve method, typical geometric conditions of $L/L_w = 11$ and $s = 1$ are selected. More modification factors for other common geometric combinations of cutoff walls were made using the program Slug_3D (Nguyen 2007). Similarly, the procedure for using the modified line-fitting method for vertical cutoff walls (Choi and Daniel 2006a) can be utilized to determine the hydraulic conductivity except for using Equation (1).

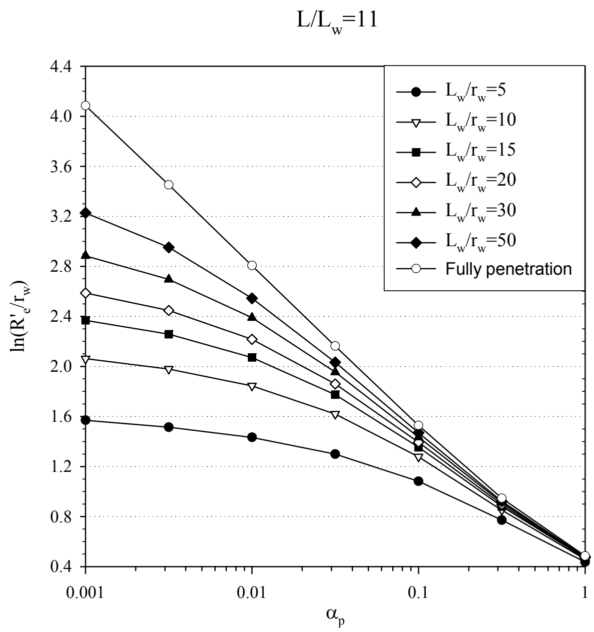

Fig. 4. Values of $\ln(R_e'/r_w)$ for aquifer case)

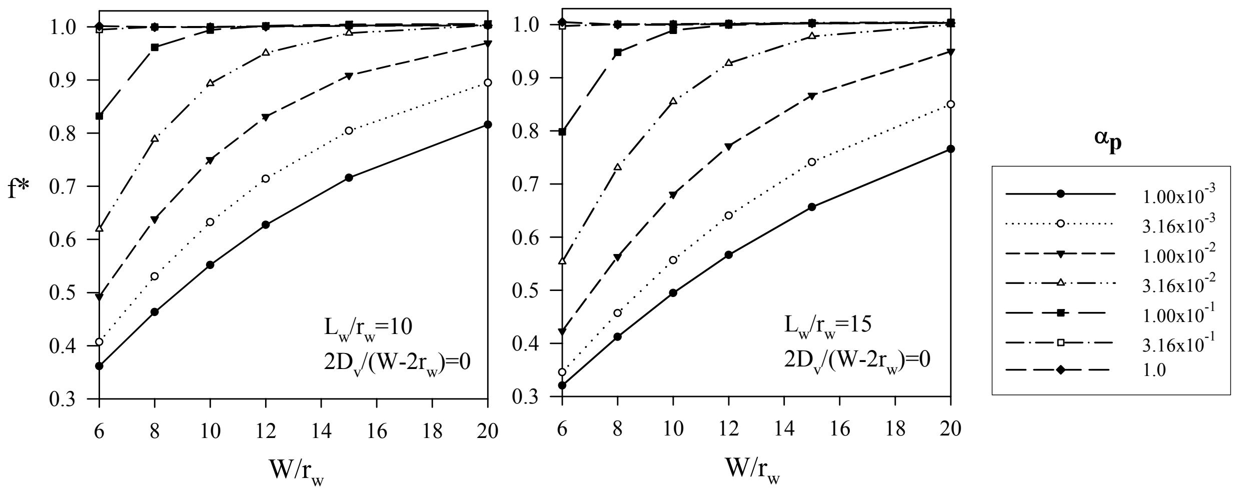

Fig. 5. Some typical modification factors *f** for the case of the existence of filter cake (L/L_w = 11 and s = 1)

5. Case Study

The methods proposed in this study for estimating hydraulic conductivity of a cutoff wall considering the presence of filter cake were employed to reanalyze the case study from EMCON (1995). This case study had been performed by Choi and Daniel (2006a) with no consideration of filter cake. The case study involves slug test response data from the cutoff walls constructed in the early 1990s at the West Contra Costa Sanitary Landfill in Richmond, California. More information can be found in Choi and Daniel (2006a). The specification required a soil-cement-bentonite backfill with hydraulic conductivity less than or equal to 1×10^{-8} m/s. Hydraulic conductivity of reconstituted samples ranged widely from 1.0×10^{-8} to 2.0×10^{-6} cm/s, and hydraulic conductivity of relatively undisturbed samples ranged from 6.0×10^{-7} to 4.0×10^{-6} cm/s for the M-11/15 wall and 8.0×10^{-8} to 1.0×10^{-6} cm/s for the M-17/21 wall. The average specific storage was determined as 2.5×10^{-2} m^{-1} (EMCON, 1995).

Based on the geometry description of vertical cutoff walls in the landfill site, approximations of geometry for the slug test simulations were chosen and the corresponding type curves and the modification factors were determined by Choi and Daniel (2006a). In the previous case study performed by Choi and Daniel (2006a), the hydraulic conductivity of the 93-1 case was evaluated to be 2.5×10^{-8} cm/s in the type curve method and 2.6×10^{-8} cm/s in the modified line-fitting method. In the case of 94-15, the hydraulic conductivity was evaluated to be 3.0×10^{-8} cm/s in the type curve method and 3.1×10^{-8} cm/s in the modified line-fitting method. The previous results obtained by Choi and Daniel (2006a) without considerations of filter cake were also summarized in Table 1 for comparison. Hydraulic conductivity is recalculated with consideration of filter cake in this study. For example, test data and analysis procedures are presented in Figure 5 (a) and (b) for the 93-1 case. Following the matching procedures, hydraulic conductivity and specific storage were obtained and summarized in Table 1, along with EMCON's original results, which adopted the Bouwer and Rice method categorized in the line-fitting method but did not account for compressibility and geometric effects.

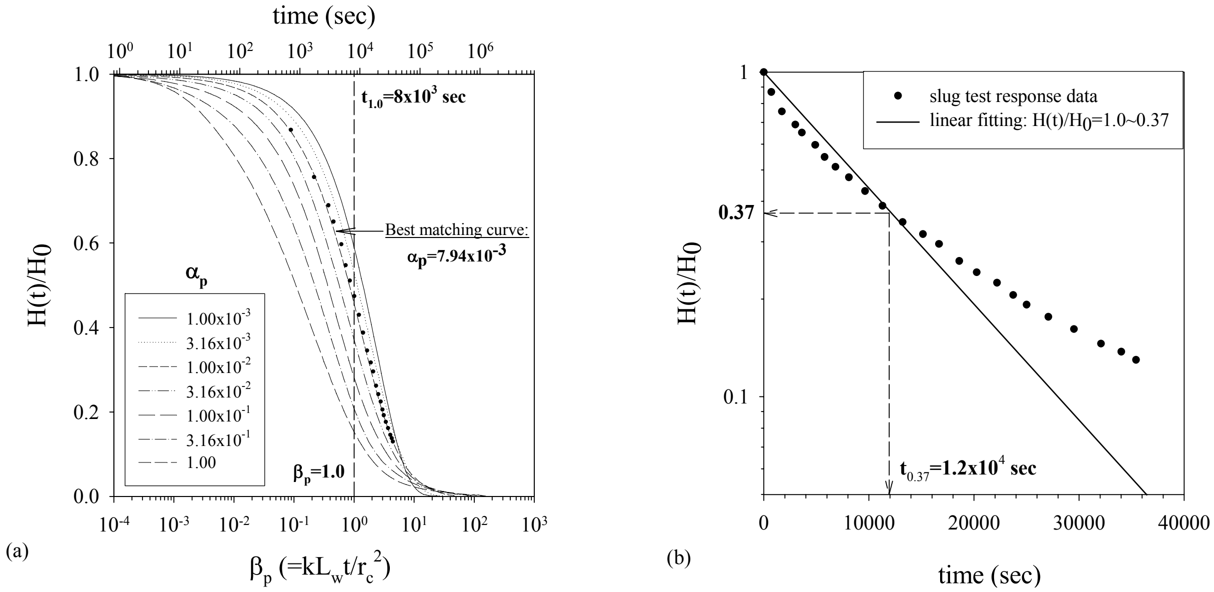

Fig. 5. Reanalyzing slug test data for Case 93-1 in the M-11/15 vertical cutoff wall
with the consideration of the effect of filter cake:
(a) Type curve method and (b) modified line-fitting method (using the basic time lag)

Table 1. Case study results of vertical cutoff walls

Case	Recommended methods								EMCON's original results	
	Type curve method				Modified line-fitting method					
Analysis with consideration of filter cake										
Case	α_p	$t_{1.0}$ at β_p =1.0(s)	S_s[a] (m^{-1})	k[b] (m/s)	$t_{0.37}$ (s)	$\ln(R_e'/r_w)$	f*	k[c] (m/s)	S_s (lab. test) (m^{-1})	k (Bouwer & Rice method) (m/s)
93-1 (M-11/15)	7.9×10^{-3}	8.0×10^{3}	3.9×10^{-4}	6.8×10^{-8}	1.2×10^{4}	1.89	0.63	6.8×10^{-8}	2.5×10^{-2}	3.0×10^{-8}
94-15 (M-17/21)	7.1×10^{-3}	2.2×10^{4}	6.2×10^{-3}	5.2×10^{-8}	3.0×10^{4}	2.13	0.82	4.9×10^{-8}	2.5×10^{-2}	4.0×10^{-8}
Analysis without consideration of filter cake (Choi and Daniel 2006a)										
Case	α_p	$t_{1.0}$ at β_p =1.0(s)	S_s[a] (m^{-1})	k[b] (m/s)	$t_{0.37}$ (s)	$\ln(R_e'/r_w)$	f	k[d] (m/s)		
93-1 (M-11/15)	1.3×10^{-1}	2.2×10^{4}	6.7×10^{-3}	2.5×10^{-8}	1.2×10^{4}	1.15	0.98	2.6×10^{-8}		
94-15 (M-17/21)	3.9×10^{-2}	4.0×10^{4}	3.5×10^{-2}	3.0×10^{-8}	3.0×10^{4}	1.71	0.92	3.1×10^{-8}		

[a] $S_s = \frac{\alpha_p}{L_w}\left(\frac{r_c}{r_w}\right)^2$ [b] $k = \frac{1.0 r_c^2}{L_w t_{1.0}}$ [c] $k = \frac{r_c^2\left[\ln\left(\frac{R_e'}{r_w}\right)/f^*\right]}{2L_w}.\frac{1}{t_{0.37}}$ [d] $k = \frac{r_c^2\left[f \times \ln\left(\frac{R_e'}{r_w}\right)\right]}{2L_w}.\frac{1}{t_{0.37}}$

As compared in Table 1, the hydraulic conductivities considering filter cake are higher than the estimates for no filter cake assumption obtained by Choi and Daniel (2006a) with both the type curve method and the modified line-fitting method (see Table 1). This difference shows the necessity of considering the filter cake in evaluating hydraulic conductivity of vertical cutoff walls.

If slug test analysis without consideration of filter cake is performed when evaluating hydraulic conductivity of vertical cutoff walls with filter cakes, evaluated values of hydraulic conductivity can be underestimated. This is because the estimated hydraulic conductivity without consideration of filter cake should be influenced not only by the backfill material itself but also by the filter cake. The estimated value in slug tests is not an overall hydraulic conductivity of vertical cutoff walls but a result of matching error due to the inappropriate consideration of wall boundaries. In addition, hydraulic conductivity of the backfill materials and the filter cake must be separately evaluated. The considerably low hydraulic conductivity of filter cake may contribute to effectively controlling ground water but also influence the result of a slug test analysis if the filter cake is not considered.

The results of the type curve method that seems more rigorous are almost the same with the results of the modified line-fitting method. This shows the efficiency of the modified line-fitting method because this method is easier to apply in practice. Different results from EMCON (1995) were obtained using the Bouwer and Rice method – a method belongs to the category of line-fitting method. These differences are caused primarily by the fact that the Bouwer and Rice method used in the EMCON's analysis ignores the compressibility of a backfill material as well as the role of vertical cutoff wall boundary.

6. Conclusions

Two methods for evaluating hydraulic conductivity of a vertical cutoff wall considering the presence of filter cake on the interface between the cutoff wall and the natural soil formation has been developed with the aid of the numerical program Slug_3D. The applicability of the type curve method was enhanced by taking into account not only the compressibility of the cutoff wall material and the boundary conditions, but also the effect of the filter cake on the boundaries of the vertical cutoff wall. The modified line-fitting method (Choi and Daniel 2006), provides an easy, effective and practical way to evaluate hydraulic conductivity of a compressible vertical cutoff wall with consideration of filter cake. Prior to utilizing the methods, the D_{15} size of the natural ground and the d_{85} size of slurry if the slurry contains suspended soil particles need to be checked to decide whether the filter cake should be considered or not, according to Filz et al. (1997) and Henry et al. (1998). If not, the proposal of Choi and Daniel (2006) for the case of no filter cake should be used.

To illustrate the application and efficiency of the proposed methods, a case study involving two slug tests in vertical cutoff walls at a landfill site was considered. A comparison of the results from Choi and Daniel (2006a), which were obtained without consideration of filter cake and the new results in this study was made to prove the effect of filter cake in estimating hydraulic conductivity through a slug test and the necessity of considering this effect. Considering the filter cake in the slug test analyses for the cases of vertical cutoff walls helps avoid misunderstanding the actual hydraulic conductivities.

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