DISCUSSION

A constant-head pumping test method using direct-push equipment for in situ hydraulic conductivity measurements

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The authors (Kobayashi *et al.*, 2012) have made a valuable contribution to the growing literature on hydraulic testing with direct-push equipment. The purpose of this discussion is to draw attention to only one aspect of their work, the development of the shape factor for estimating the hydraulic conductivity. This area is of continuing interest to geotechnical engineers and hydrogeologists and has received greater scrutiny as shorter testing intervals have been adopted for testing with direct-push equipment, self-boring permeameters and packers (Ratnam *et al.*, 2005; Mathias & Butler, 2007).

When assessing shape factors developed with numerical models, it is particularly important to ensure that the simulated geometry conforms to the test configuration. For the technique of Kobayashi *et al.* (2012), the appropriate idealisation appears to be the M1 geometry of Ratnam *et al.* (2001), reproduced in Fig. 14. With the M1 geometry, there is neither flow out of the bottom of the test interval, nor is there flow back into the borehole some distance above and below the test interval. In this case, as the length of the test

interval approaches zero so must the flow. The Ratnam *et al.* (2001) regression equation (4) proposed for the M1 geometry matches this expected result. By contrast, the regression equation proposed by Kobayashi *et al.* (2012) predicts that as the aspect ratio L/D approaches zero, the shape factor approaches a value $F/D = 1.984$, where L and D are the length and diameter of the test interval, respectively, and F is the shape factor.

The results of the simulations reported by Kobayashi *et al.* (2012) and their regression equation (3) are plotted in Fig. 15, along with the regression equation of Ratnam *et al.* (2001) and the results from the numerical modelling of Al-Dhahir & Morgenstern (1969) and Tavenas *et al.* (1990). There are subtle differences between the shape factors; these differences are more evident in the expanded view shown in Fig. 16. It is not clear which set of results is most reliable; however, it is clear that a definitive shape factor must be both faithful to the results of high-resolution numerical models and to the limiting result that $F/D \rightarrow 0$ as $L/D \rightarrow 0$. It is hoped that this comment motivates further analyses of this interesting and important problem.

Authors' reply

The authors would like to thank Mr Neville for his interest in their paper. His discussion concerns the development of the shape factor for short testing intervals. As he pointed out, with the M1 geometry, as the aspect ratio L/D approaches zero so must the flow rate Q , regardless of the magnitude of the pumping-induced head difference H . It is evident also from Fig. 11 (Kobayashi *et al.*, 2012) that the

Fig. 14. Geometry for the Ratnam *et al.* (2001) shape factor M1

Fig. 15. Comparison of shape factors

Fig. 16. Expanded view of shape factors for relatively short screens

Q/H ratio decreases with decreasing L/D , and that it will finally become zero when $L/D = 0$. The hydraulic conductivity k is determined by dividing the Q/H ratio by the shape factor F , suggesting that F must also vary with respect to the variation in the Q/H ratio. It should, therefore, be concluded that $F \rightarrow 0$ as $L/D \rightarrow 0$. The authors acknowledge that the following equation proposed in their paper is unreasonable given the fact mentioned above and may result in the underestimation of k when the testing interval is relatively short.

$$\frac{F}{D} = 1.013 \frac{L}{D} + 3.859 \sqrt{\frac{L}{D}} + 1.984 \quad (5)$$

The regression curve (5) was drawn with respect to the finite-element method solutions that were calculated in the range of $0.33 < L/D < 16$ (Table 1, Kobayashi *et al.*, 2012). It should be noted that F/D will become less than 1.984 if the finite-element calculation is performed for the conditions of $L/D < 0.33$. In this discussion, a new regression curve that passes through the origin of the $(F/D)-(L/D)$ coordinates was drawn with respect to the same finite-element method solutions. The regression equation can be given as

$$\frac{F}{D} = 0.557 \frac{L}{D} + 5.971 \sqrt{\frac{L}{D}} \quad (6)$$

It can be said that this equation agrees fairly well with the following equation of Ratnam *et al.* (2001)

$$\frac{F}{D} = 0.569 \frac{L}{D} + 5.243 \sqrt{\frac{L}{D}} \quad (7)$$

The finite-element method solutions and the regression equation (6) for a relatively short screen ($L/D < 5$) are plotted in Fig. 17, along with the regression equations (5) and (7) and the solutions by Brand & Premchitt (1980), which showed good agreement with equation (1) of Kobayashi *et al.* (2012). It is evident from the figure that, when $L/D < 1$, equation (5) is in better agreement with the finite-element method solutions than equation (6). In fact, the regression coefficient R^2 dropped from 0.999 for equation (5) to 0.996 for equation (6). This indicates that, for the cases when $L/D > 0.33$, equation (5) provides better k estimates than equation (6).

Fig. 17. Relationships between normalised shale factor and aspect ratio for relatively short screens

Figure 4 of Kobayashi *et al.* (2012) was reproduced in Fig. 18 based on equation (6); in other words, Fig. 18 shows the ratio of the intake factors of equation (5) and those proposed by other researchers (Hvorslev, 1951; Wilkinson, 1968; Brand & Premchitt, 1980; Chapuis, 1989; Ratnam *et al.*, 2001) to equation (6). This figure indicates that equation (7) by Ratnam *et al.* (2001) gives a slightly smaller F compared to equation (6) and that the difference is within a range of 10% throughout the full range of aspect ratio, whereas the differences between equation (6) and the other solutions become significant when L/D is less than 1. The disparity seems to be attributable to the difference in the boundary conditions of the intake screen; equations (6) and (7) assume a closed-end cylindrical model (M1 geometry), while the other solutions assume an open-ended cylindrical model (using a screen with a permeable bottom).

In conclusion, it should be emphasised again that the regression equation for the closed-end cylindrical model must imply that $F/D \rightarrow 0$ as $L/D \rightarrow 0$, and therefore, equation (6) is logically sound, rather than equation (5). On the other hand, it can also be said that equation (5) provides shape factors that are more faithful to the finite-element method solutions when $L/D > 0.33$.

The authors performed the finite-element calculations under axisymmetric conditions, as did Ratnam *et al.* (2001), and therefore, both the solutions should coincide if Ratnam *et al.* (2001) used the same seepage governing equation. It appears that possible factors causing the difference between equations (6) and (7) are differences in the numerical

Fig. 18. Comparison of shape factors

techniques, including the finite-element domain size and numerical resolution. An additional examination of this problem is not given here, since it seemed to be irrelevant to the point of this discussion.

As shown in Fig. 18, there is only a slight change in most of the shape factors with increasing aspect ratio when $L/D > 2$, with the values generally being within a range of $\pm 20\%$, whereas the differences become prominent when $L/D < 2$. This suggests that practitioners should keep in mind that the k estimate varies greatly depending on which shape factor is being used when performing tests with extremely short testing intervals. As the discussor pointed out, it is of interest and important to make clear which solution is most reliable for short testing intervals; however, from a practical viewpoint, it is advisable to keep the intake screen longer than $L/D = 2$ to ensure the reliability of the hydraulic conductivity estimation.

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