Evaluating the effects of clay and gas compressibility during field permeability tests

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ABSTRACT
Variable-head permeability tests in soft soils with low hydraulic conductivity are frequently conducted without measuring the volume of water either added (falling-head test) or withdrawn (rising-head test) from the observation well. When this volume is measured, it is often found to differ from the volume calculated using the riser pipe section and the initial change in water height. Air storage effects and cavity deformation phenomena are generally considered to be the cause of this discrepancy. This paper first establishes a set of differential equations which can be solved to analyse test data where those two phenomena cannot be neglected. Cavity deformation and gas compressibility can also be evaluated in the field using a simple testing method presented herein. During this test, a known volume of water is either added to, or removed from a riser pipe, and compared to the volume calculated using the pipe section and the water height change. Typical test data are presented. It is shown that the two types of volume change will lead to underestimating the hydraulic conductivity during permeability tests and that this error is magnified when a riser pipe with a small diameter is used.

RÉSUMÉ
On mesure rarement le volume d'eau ajouté ou retiré d'un piézomètre au cours d'un essai de perméabilité à charge variable, réalisé dans un matériau peu rigide ayant une faible perméabilité. Lorsqu'on mesure ce volume, il diffère généralement du volume calculé avec le changement de hauteur d'eau dans le tubage et l'aire de la section de ce dernier. On peut expliquer cette différence par la déformation de la cavité à la base du piézomètre et par la compression ou la dilatation des bulles d'air présentes dans la zone filtre. Ce compte-rendu présente tout d'abord un système d'équations différentielles qui peut être résolu pour analyser les résultats d'essais pour lesquels ces deux changements de volume ne peuvent être négligés. La déformation de la cavité à la base du piézomètre et la compression des bulles de gaz peuvent aussi être évaluées par un test simple qui consiste à ajouter ou retirer du tubage du piézomètre un volume déterminé d'eau. Ce volume est ensuite comparé au volume calculé avec la section du tubage et le changement de niveau d'eau à l'intérieur de celui-ci. Des résultats types pour cet essai sont présentés. Il est démontré que ces deux types de déformation induisent une sous-estimation de la perméabilité et que cette erreur est plus grande lorsque les essais sont réalisés avec un tubage de faible diamètre.

1 INTRODUCTION

The hydraulic conductivity of a soft clay aquitard can be evaluated with several field methods. This paper looks at in situ falling-head and rising-head permeability tests conducted in observation wells. Different sources of error in conducting and interpreting this type of test have been reported in the literature (Bjerrum et al. 1972; Chapuis 1989; Chapuis and Sabourin 1989; Chapuis et al. 1981; Keller and van der Kamp 1992). This paper deals only with interpretation errors linked to two instantaneous volume changes occurring when the height of water in a riser pipe changes.

The first type of instantaneous volume change is the result of air compressibility. If gas bubbles are present in the filter zone, their volume responds to change in water height. If the water level rises, they contract, otherwise they expand. There are several ways for air to get entrapped in the filter zone. Air bubbles can move into the portion of the filter zone between the top of the screen and the top of the cavity if the water level is lowered to the screen. Air bubbles can also be present in the sand used to fill the filter zone when it is poured in the borehole. Volume change related to the presence of gas bubbles was previously discussed by Keller and van der Kamp (1992) and Chapuis (2005).

A second type of volume variation is caused by the filter zone wall response to change in total stress. If the water level rises, the observation well cavity expands, otherwise, it contracts. Cavity volume change can be shown to be inversely proportional to the shear modulus (G). Undrained cavity expansion following a change in total stress has been extensively studied with the development of the pressuremeter test. Baguelin et al. (1978) gave typical values of pressuremeter shear modulus (G_M) for clay aquitards. For soft to firm clays, G_M can be expected to lie somewhere between 1 and 10 MPa. For the small changes in total stress encountered during the falling- and rising-head permeability test, we can expect the cavity wall to have a G_M value closer to the maximum shear modulus (G_{max}). G_M is usually smaller than G_{max} as the former is calculated for relatively high strain level (clay is not a linearly elastic material). Recent pressuremeter test results presented by Silvestri (2003) gave G_{max} values ranging from 5 to 15 MPa for a Champlain clay deposit near Louiseville, Quebec. We must also bear in mind that the drilling method used for the installation of the observation well can lower the value of the modulus (Baguelin et al. 1978). Therefore, G values can be quite variable depending on the type of clay, the drilling method used and the extent of the water height change.

The main objectives of this paper are 1) to assess, both theoretically and in the field, the magnitude of cavity and gas bubbles volume changes, 2) to evaluate the effect of these two phenomena on hydraulic conductivity measurements and 3) to set forth guidelines for choosing a riser pipe diameter and filter zone geometry for observation wells installed to run permeability tests in soft clays. As we will show, using a small riser pipe diameter and a large filter zone magnifies the effect of cavity deformation and gas volume change and, in some cases, can hamper the interpretation of permeability test data.

2 THEORY

In this section, we develop a general set of differential equations which take into account gas bubbles and cavity volume changes and the flow of water in and out of the aquitard. Symbols used in the demonstration are defined in Figure 1. We consider only radial deformations. We assume that the aquitard behaves as an elastic material with respect to changes in total pressure. We take for granted that gas bubbles are sufficiently large for the mean pore water pressure (u_w) to be equal to gas pressure (p_g), the small difference between water and gas pressure being equilibrated by local interfacial tension.

Gas volume can be expressed using the unsaturated zone dimensions, porosity (n) and degree of saturation (S_r) (Equation 1).

$$V_g = \frac{n(1-S_r)\pi(D^2 - d_{out}^2)L_g}{4} \quad [1]$$

Where L_g is the height of unsaturated sand in the observation well filter zone, d_{out} is the outside diameter of the riser pipe and D is the filter zone diameter. Gas volume can also be expressed using Boyle's law (Equation 2).

$$p_g V_g = p_{g0} V_{g0} \quad [2]$$

We get Equations 3 and 4 by differentiating Equations 1 and 2.

$$dV_{g1} = \frac{n(1-S_r)\pi(D^2 - d_{out}^2)}{4} dL_g + \frac{n(1-S_r)\pi D L_g}{2} dD \quad [3]$$

$$dV_{g2} = \frac{-V_g}{p_g} dp_g \quad [4]$$

Where p_g is the absolute gas pressure at the center of the unsaturated zone. In Equation 4, the absolute pressure value and increment can be replaced by expressions based on the hydraulic charge difference between the riser pipe and the soil surrounding the filter zone (H), the water column height when H=0 (y_0), the atmospheric pressure (p_{atm}) and L_g (Equation 5).

$$dV_{g2} = -\frac{V_g \gamma_w}{p_{atm} + y_0\gamma_w + 0.5\gamma_w L_g + H\gamma_w} dH - 0.5 \frac{V_g \gamma_w}{p_{atm} + y_0\gamma_w + 0.5\gamma_w L_g + H\gamma_w} dL_g \quad [5]$$

Cavity volume can be expressed as a function of its diameter and length (Equation 6).

$$V_{cavity} = \frac{\pi D^2 L}{4} \quad [6]$$

Assuming that the cavity length is constant, we get Equation 7 by differentiating Equation 6.

$$dV_{cavity1} = \frac{\pi D L}{2} dD \quad [7]$$

If we suppose that the soil surrounding the observation well is an infinite medium and has a linearly elastic undrained response to change in total stress, change in cavity volume can also be expressed using Lamé's (1852) equation (Equation 8).

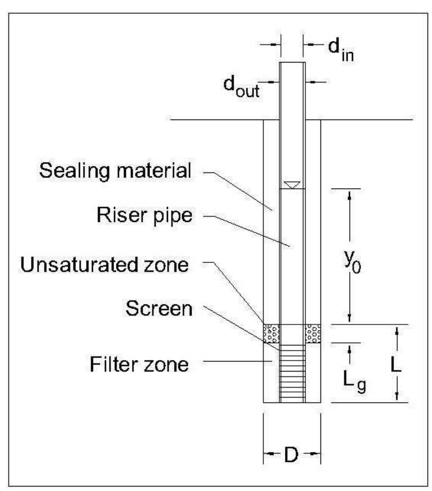

Figure 1. Symbols used in the demonstration

$$dV_{cavity2} = \frac{L\pi D^2 \gamma_w}{4G} dH \qquad [8]$$

The volume of water flowing either in or out of the aquifer can be calculated using Equation 9 (Hvorslev 1951). For filter zones with 1 ≤ L/D ≤ 8, the shape factor (c) can be calculated using the spherical approximation (Equation 10) while the ellipsoid formula (Equation 11) can be used for filter zone where L/D ≥ 4 (Chapuis 1989). The filter zone length is chosen assuming that the hydraulic conductivity of the unsaturated zone is sufficiently low with respect to the rest of the filter zone to prevent water from flowing into it.

$$dV_{flow} = -cKHdt \qquad [9]$$

$$c = 2\pi D\sqrt{\frac{(L-L_g)}{D} + \frac{1}{4}} \qquad [10]$$

$$c = \frac{2\pi(L-L_g)}{\ln\left(\frac{2(L-L_g)}{D}\right)} \qquad [11]$$

Change of water volume stored in the riser pipe can be expressed using Equation 12.

$$dV_{pipe} = \frac{\pi d_{in}^2}{4} dH \qquad [12]$$

Finally, we can write a mass balance equation comparing the volume of water leaving or entering the aquitard (dV_{flow}), cavity volume change (dV_{cavity}), gas volume change (dV_g), change in the volume of water stored in the riser pipe (dV_{pipe}) and water added in the riser pipe (dV_{slug}). We then get a system of 3 equations (Equations 13 –15) which must be solved for every time step. The three unknowns are dH, dD and dL_g.

$$dV_{cavity1} = dV_{cavity2} \qquad [13]$$

$$dV_{g1} = dV_{g2} \qquad [14]$$

$$dV_{pipe} + dV_{cavity1} - dV_{g1} = dV_{flow} + dV_{slug} \qquad [15]$$

This set of equations can easily be solved numerically with Matlab for various sets of initial conditions and dV_{slug} schedules. Two types of simulation will be studied in this paper. The first type reproduces variable-head permeability tests with cavity and gas volume changes. For these simulations we start with an initial H value and the dV_{slug} term of Equation 15 is equal to 0 for each time step. The second type of simulation is meant to reproduce the simple testing method introduced in the next section. These simulations use a slug schedule and have a shorter duration than those of the first type.

3 A SIMPLE TESTING METHOD

Cavity deformation and gas volume change can be evaluated using a simple testing method. Known volumes of water are either poured into a monitoring well using a graduated cylinder or removed using a peristaltic pump and the same cylinder. Deformation can be evaluated by measuring the water level change in the riser pipe and by comparing it with a theoretical level change calculated using the volume of water added and the riser pipe inner diameter. The difference between the measured level change and the theoretical level change multiplied by the section of the riser pipe equals the sum of the changes in cavity and gas volumes. This method is relatively straightforward but some pitfalls must be avoided.

Knowing the real riser pipe diameter can sometimes be an issue when we need to compare theoretical and experimental water level changes. The real inside diameter of a pipe generally differs from the nominal diameter. For example, ASTM standard D1785 for PVC pipes states that the inside diameter of a 2 inch schedule 40 pipe can vary between 52.65 and 51.33 mm. One must also consider that a certain amount of out-of-roundness is tolerated in the standard and that the real diameter may vary along the length of the pipe.

Measuring precisely the real riser pipe diameter in the field can sometimes be difficult. It can usually be achieved by inflating a packer in the riser pipe, thus preventing cavity deformation and air storage effects, and by using the same procedure as when measuring deformation. Measuring the real diameter in the field can be avoided by using a pipe whose section has been calibrated in a laboratory. If the water level in the observation well is sufficiently close to ground surface, the calibrated pipe can be added directly on top of the riser pipe. Alternatively, if the water level is too far down, the calibrated pipe can be attached on top of a packer (Figure 2). The calibrated pipe diameter can be evaluated by comparing the weight of the dry pipe and the weight of a known length of pipe filled with deaired and demineralised water. If a calibrated pipe is used, care must be taken to avoid hydraulic fracturing of the soil around the cavity by imposing on it too large a change in water level and total stress (Bjerrum et al. 1972).

Figures 3 and 4 present typical results for the testing procedure together with numerical results obtained with Equations 13 to 15. The difference between the cumulative slug volume and cumulative change in water volume stored in the riser pipe (dV, Equation 16) is plotted against cumulative slug volume. At the beginning of the test, both V_{slug} and dV are equal to 0. The tests were conducted in two observation wells installed in a

Champlain clay aquitard located near Lachenaie, Quebec. Characteristics of the observation wells and of the tests are presented in Table 1.

$$dV = \sum dV_{slug} - \left(H - H(t_0)\right)\frac{\pi d_{in}^2}{4} \qquad [16]$$

Even if equal volumes of water were added and removed from the riser pipe, both tests ended with positive dV values (Figures 3 and 4). This implies that the water level in the riser pipe at the end of the test was lower than the initial water level. This difference can have several causes. First, as the hydraulic head difference between the well and the clay aquitard was positive for most of the test duration and for both wells, some water has flowed out of the well into the aquitard. A positive dV value could also be caused by permanent deformation. It is likely that undrained cavity expansion is not a completely elastic phenomenon. Change in gas volume could also explain the different initial and final water levels. For example, some gas could have gone into solution in the water. Finally, errors in volume and water level measurements may also lead to a final dV value different from 0.

The numerical results presented in Figure 3 allow us to evaluate the hypothesis of the final dV value being caused by water flowing out of the observation well. For both wells, regular falling-head permeability tests were conducted before the simple deformation tests. Both wells had hydraulic conductivities approaching $5X10^{-10}$ m/s. Numerical simulations based on these values gave a final dV on the order of 1 cm^3 (solid curve in Figure 3). To get a final value of 50 cm^3, as with the experimental data, the hydraulic conductivity would have to be around $2X10^{-8}$ m/s (dashed curve in Figure 3). This value appears unrealistically high for a Champlain clay aquitard.

It is unlikely that the final dV values of Figures 3 and 4 are only due to random measurement errors since the data plots on relatively straight lines for both phases of the tests (volume-removing or volume-adding). Measurement errors could result in two approximately straight lines if errors were strongly biased in one of the two phases of the test. Such a bias could be observed if different methods were used to measure the water

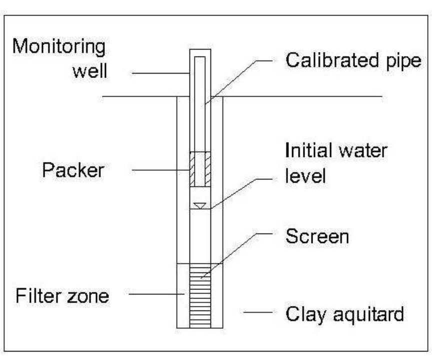

Figure 2. Using a calibrated pipe to evaluate cavity and gas volume change

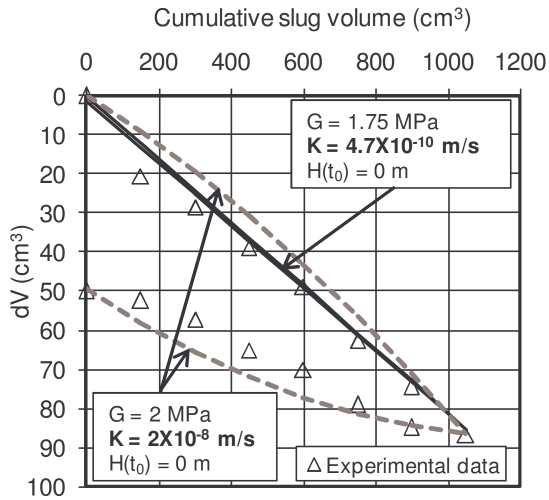

Figure 3. Comparison between test results for the first observation well and two curves obtained numerically for two K values.

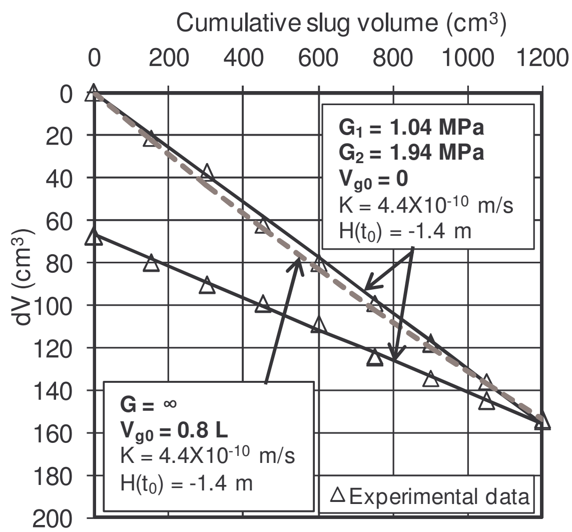

Figure 4. Comparison between test results for the second observation well and numerical simulations with cavity deformation or air storage effect scenarios

Table 1. Characteristics of the observation wells

	Well 1	Well 2
D (mm)	73.1	73.1
L (mm)	1195	1195
d (mm)	20.25	20.25
y_0 (m)	4.8	5.0
$H(t_0)$ (m)	0.0	-1.4
K (m/s)	$4.7 X 10^{-10}$	$4.4 X 10^{-10}$
dV_{slug} (cm^3)	150	150
Δt between slugs (s)	60	60

volumes during the two phases. This is not the case for the data presented in Figures 3 and 4.

For the first and second well, respectively 50 and 70 cm^3 of gas would have to go into solution for the final dV value to be explained by this cause alone. Air in solution makes up about 2 % of the total water volume (Fredlund and Rahardjo 1993). For the different numerical simulations presented in Figures 3 and 4, the volume of air in solution in water contained in the filter zone and inside the screen is less than 50 cm^3. Thus, the mass of air in solution would have to at least double during the test to account for the final dV value. Furthermore, the diffusion of gas into water would have to occur quickly (the total test duration is about 15 minutes). For these reasons air dissolution does not appear to be the cause of the final dV value and permanent deformation is the only logical explanation which can account for the final dV value. This implies that G takes different values for rising and falling water levels. For Figures 3 and 4, the modulus of the second phase of the test (G_2) is approximately twice the modulus of the first phase (G_1).

The results of numerical simulations can also be drawn on to show that cavity expansion and air storage effects can theoretically explain equally well the deformation observed with the simple testing method. The water-adding parts of the two sets of numerical results presented in Figure 4 are almost undistinguishable. The solid curve is based on the assumption that the filter zone is free of gas and that G_1 and G_2 are respectively 1.04 and 1.94 MPa. The dashed curve is computed assuming that the clay is infinitely rigid but that the filter zone initially contains 0.8 L of gas. Even if both curves fit the data, from a practical standpoint, it is doubtful that the observed dV data are caused solely by gas compressibility. To contain 0.8 L of air, approximately half of the filter zone would need to be markedly unsaturated (S_r=0.1). Also, it is difficult to explain the final dV value if we rely on gas compressibility to explain the difference between theoretical and measured water level changes.

The G values found to best fit the data of Figures 3 and 4 are 3 to 5 times lower than the G_{max} values found by Silvestri (2003) for similar Champlain clays. The drilling method used for the installation of the observation wells is probably not the cause of the apparent clay softness as for both observation wells 1 and 2, the cavity was cut using a thin wall sampler in order to minimize remolding. Oedometer tests conducted by Benabdallah (2005) on clay of the same Lachenaie region gave G values varying between 0.66 and 1 MPa. These results tend to indicate that the G values used for the simulations of Figures 3 and 4 are realistic.

Using Equations 13 to 15, one could program an algorithm based on the least squares method to fit optimal G, K, $H(t_0)$ and L_g values to test results. However, as previously discussed, L_g and G cannot be optimised simultaneously as an infinite number of solutions would be generated. Equations 13 to 15 could also be programmed to use different modulus values for rising and falling water levels. The optimised parameters would then be (G_1, G_2, K, H(t=0)).

4 EFFECT ON HYDRAULIC CONDUCTIVITY MEASUREMENTS

Equations 13-15 can be used to study numerically the effect of clay deformation and gas compressibility on permeability test results. Figures 5 and 6 present simulated test results for conditions meant to reproduce those of the second observation well. The same gas volume and G value scenarios as those presented in Figure 4 have been used. Results of the field test for this well are also shown on Figures 5 and 6. For both numerical solutions, the K value was chosen to obtain the same slope as the experimental data. The apparent K value was calculated using the slopes of the ln(H) vs. t curve and the velocity graph, as one usually does to interpret variable-head test data.

It is worth noting that both cavity deformation and air storage effects result in approximately linear ln(H) vs. t and velocity graph curves. Therefore, the results of a variable-head test cannot be used to assess the importance of cavity and gas volume changes. The curvature at the beginning of the velocity graph for the experimental data is considered to be caused by delayed deformation (consolidation). This phenomenon is not modeled by Equations 13-15.

The difference between apparent and real K values implies that the usual interpretation methods may underestimate K. For a rising-head test, when the water level rises by 1 m, the volume of water which has flowed from the surrounding soil into the observation well is equal to the increase in volume of water stored in the riser pipe plus the volume of water needed to fill the cavity expansion. On the other hand, for the falling-head test, the volume of water flowing out of the well has to be

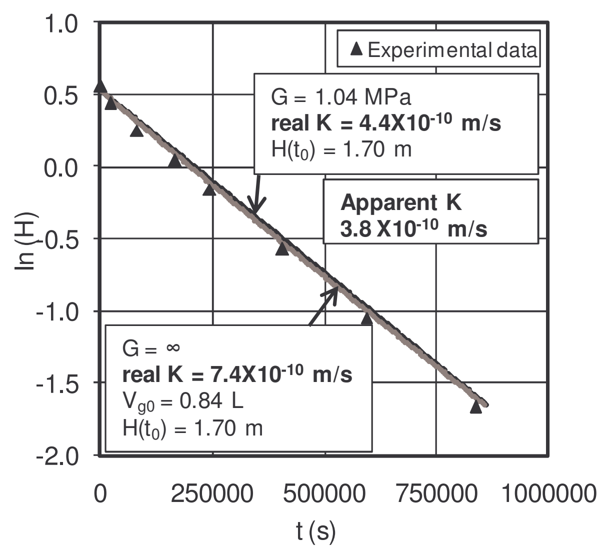

Figure 5: Plot of ln(H) vs. t for numerical simulations and experimental data resulting in an apparent K value of $3.8X10^{-8}$ m/s.

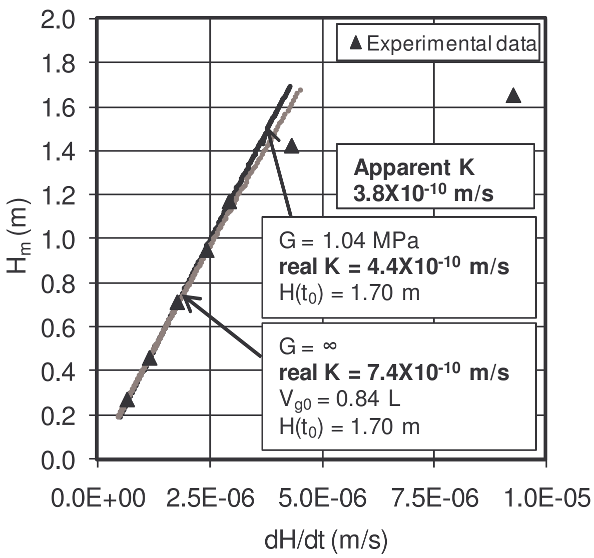

Figure 6: Velocity graph for numerical simulations and experimental data resulting in an apparent K value of $3.8X10^{-8}$ m/s.

equal to the change in volume of water stored in the riser pipe plus the volume lost to cavity volume shrinkage. In both cases, more water has flowed in or out of the well than what the change in water height indicates. The difference is even more noticeable when gas bubbles are present. In such cases, more water has flowed in or out of the well than indicated by the change in water level for the riser pipe. Furthermore, the shape factor may be overestimated because of the unsaturated zone.

A direct consequence of this distinction between apparent and real K values is that the former will be a function of the riser pipe diameter. For a given change in water height, the cavity volume change depends only on water pressure and thus it is the same whether we use a 5 mm or 50 mm riser pipe. When a smaller pipe is used, change in cavity volume will become larger when compared to change in water volume stored in the riser pipe. Using a smaller riser pipe will magnify the error described before and hydraulic conductivity will be underestimated. Figure 7 shows the relation between riser pipe diameter and apparent hydraulic conductivity for the cavity deformation scenario (G=1.04 MPa) of Figures 4 to 6. It must be noticed that using a very small riser pipe (≤ 5 mm) can result in an apparent K an order of magnitude lower than the real K value.

Since cavity deformation is proportional to total cavity volume (Equation 8), using a larger cavity will have the same effect as using a smaller riser pipe. The change in cavity volume will become large with respect to the change in water volume stored in the riser pipe.

When measuring the hydraulic conductivity of a clay aquitard, it is better to steer clear of cavity and gas deformation (i.e. one wants water level change due to gas and cavity deformation to represent a small percentage of the total water level change). Riser pipe diameter and filter zone geometry can be chosen to minimize gas and cavity volume change. Using a riser pipe with a smaller diameter and a larger cavity will result in shorter tests but deformations will be more important.

Before the installation of an observation well, a chart similar to the one presented in Figure 8 can be used to select cavity geometry (L and D) and riser pipe diameter combinations for which cavity volume change will have a negligible effect on the interpretation of permeability test data. The chart is drawn using Equations 8 and 12 and by assuming that $dV_{cavity} / dV_{pipe} = 0.10$. Curves are drawn for different G values. If the cavity volume – riser pipe diameter combination is located to the left of the curve for the proper G value, it is likely that cavity deformation will have an impact on test results. The value of G can be estimated using previous pressuremeter tests conducted in the same type of material and by factoring in the type of method used for drilling. It can also be estimated with the simple testing procedure described in section 3.

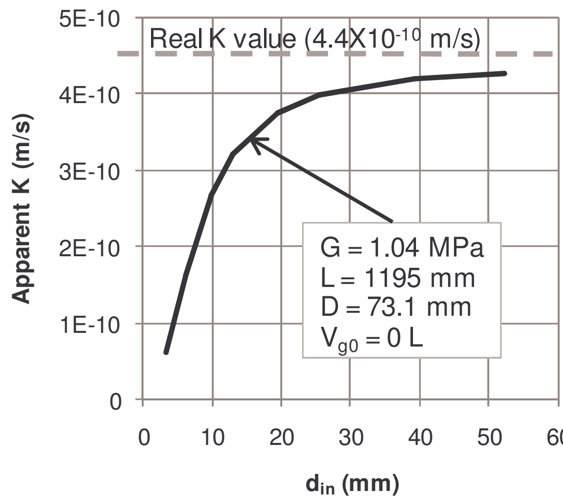

Figure 7: Apparent hydraulic conductivity as a function of riser pipe diameter.

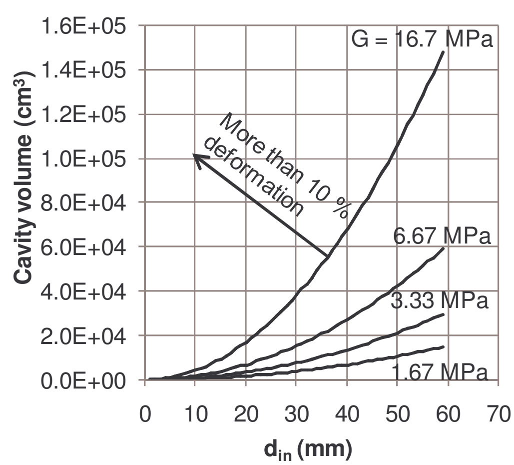

Figure 8 : Filter zone volumes and riser pipe diameters resulting in dV_{cavity}/dV_{pipe} = 10% for different undrained shear modulus.

5 CONCLUSION

Both theoretical and field methods to estimate the impact of cavity and gas volume changes on variable-head permeability test results have been presented in this paper. Cavity deformation and gas compressibility have been shown to be important sources of error in the interpretation of permeability tests for soft clays. The magnitude of the error depends on observation well geometry and on soil rigidity. Volume changes are magnified when using a riser pipe with a small diameter or a cavity with a large volume. Selecting too small a riser pipe or too large a cavity can result in underestimating K by one order of magnitude.

Further studies on this topic should try to consider both instantaneous and delayed deformations (consolidation). A set of differential equations similar to the one presented in this paper (Equations 13-15) but taking into account both types of deformations could help model both the linear and curved parts of the velocity graph. Such a model could also help to estimate parameters (e.g. c_v) not usually obtained from variable-head permeability tests.

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