Performance of fully grouted piezometers subjected to transient flow conditions

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Piezometers can be installed within clay layers with either the fully grouted or traditional method. With fully grouted piezometers, there is no sand filter around the piezometer and the borehole is grouted completely after having positioned the transducer. Advocates of this method claim that it has the following advantages: no risk of failure for the sand pack of deep wells, ease of installation, and reduced installation costs, especially from the opportunity to install several piezometers and geotechnical instruments within the same borehole. This paper presents a numerical model using the finite element code SEEP/W to assess the performance of a fully grouted piezometer under transient flow condition. The results indicate that the fully grouted transducer provides representative pore pressure data, without producing a significant piezometric error, when the permeability contrast between grout and surrounding clay is between 10^{-1} and 10. For a grout with a much lower permeability than the surrounding clay, the cement-bentonite grout should be stiffer than the clay to provide representative pore pressure data.

RÉSUMÉ
Les piézomètres peuvent être installés dans les couches d'argile avec la méthode traditionnelle ou avec un scellement complet. Avec la méthode du scellement complet, il n'y a pas de filtre granulaire autour du piézomètre et le forage est entièrement scellé après avoir mis en place le capteur. Les partisans de cette méthode affirment qu'elle a les avantages suivants : aucun risque de rupture pour les filtres granulaires des puits profonds, une facilité d'installation et des coûts d'installation réduits, particulièrement en raison de la possibilité d'installer plusieurs piézomètres et instruments géotechniques dans le même forage. Cet article présente un modèle numérique basé sur le code d'éléments finis SEEP/W pour évaluer les performances des piézomètres complètement scellés en présence d'un écoulement transitoire. Les résultats indiquent que les capteurs complètement scellés fournissent des pressions interstitielles représentatives, sans introduire une erreur piézométrique significative, lorsque le rapport entre les perméabilités du matériau de scellement et de l'argile environnante est entre 10-1 et 10. Pour un matériau dont la perméabilité est beaucoup plus faible que celle de l'argile du dépôt, le mélange de ciment-bentonite doit être plus rigide que l'argile pour fournir des valeurs représentatives de la pression interstitielle.

1 INTRODUCTION

The fully grouted technique to install pneumatic or vibrating wire pressure transducers has recently received much interest from geotechnical, mining, and hydrogeology industries. In mining engineering, they are commonly used to monitor hydraulic head fluctuations caused by underground mining activities. Moreover, in geotechnical engineering, fully grouted piezometers are usually installed within clay layers to monitor the dissipation of excess pore pressure induced by several earth structures such as embankments, dikes, and earth dams. Furthermore, in hydrogeology they are deployed in clay aquitards to assess the natural pore pressure fluctuations and to estimate in situ large-scale clay properties.

The fully grouted method consists in backfilling the entire borehole with cement-bentonite grout after having lowered a pressure transducer to the desired depth without using a sand filter pack around the piezometer. This method was first proposed by Vaughan (1969). Advocates of the fully grouted method appreciate its advantages: reduced cost, shorter installation time, ease of installation of nested piezometers, no risk of failure for the sand pack of deeper wells (McKenna 1995).

Previous investigators have claimed that the grout hydraulic conductivity (K_g) is the most crucial factor in controlling the piezometric error in the fully grouted method (Contreras et al. 2008; McKenna 1995; Mikkelsen and Green 2003; Mikkelsen 2002; Vaughan 1969). For steady state seepage, Vaughan (1969) proposed that the error may be negligible for a grout with permeability up to two orders of magnitude greater than the adjacent formation permeability. Moreover, Contreras et al. (2008) with numerical modelling found an error close to zero when the grout had a hydraulic conductivity within 3 orders of magnitude of the surrounding formation. However, Marefat et al. (2014) with analytical and numerical modeling, for steady state flow, have found that the piezometeric error is greatly related to both K_g and the field hydraulic gradient (i_v). According to Marefat et al. (2014), reliable and representative pore pressure data can be obtained by a fully grouted transducer when K_g is up to one order of magnitude greater than the adjacent clay permeability (K_c).

The response time for modern diaphragm-type piezometers installed within fully grouted boreholes have been previously assessed under controlled laboratory conditions by several authors (Bayrd 2011; McKenna 1995; Mikkelsen and Slope Indicator Co. 2000; Simeoni 2012). With previous laboratory studies, it has been concluded that the response time of the fully grouted piezometer is only a matter of seconds or minutes. However, with numerical modelling, Zawadzki and Chorley (2014) obtained that the response time for a fully grouted piezometer, installed within a fractured rock and subjected to transient flow, can be on the order of hours compared to the almost instantaneous response of a piezometer installed within a sand filter.

When fully grouted piezometers are planned to monitor a low permeability formation (intact clay aquitards or man-made clay liners), a cement-bentonite grout mix with appropriate characteristics has to be prepared to provide representative pore pressure data. This task is less trivial than it might seem. Because the clay layer has a low permeability and a low compressibility, the transducer responds with a "lag" time (Chapuis 2009a). For example, consider a grout with a lower permeability than the adjacent clay: it induces an extra time lag (McKenna, 1995). On the other hand, a grout with a higher permeability than the adjacent clay acts as a flow conduit and yields a piezometric error. Furthermore, the grout compressibility (m_{vg}) also may influence the piezometer response time. Nevertheless, K_g is not the sole factor controlling error and response time. The grout compressibility may also have some influence.

This paper analyzes the performance of fully grouted transducers when pore water pressures are measured within a clay layer under transient flow conditions. The influence of grout hydraulic conductivity and grout stiffness or compressibility on piezometric error has been investigated with numerical modelling. This paper also reviews some previously published data regarding the hydraulic conductivity and unconfined compressive strength of cement-bentonite grouts.

2 ORIGIN OF THE PIEZOMETRIC ERROR

Two criteria should be satisfied by a successful piezometer installation: 1) the piezometric error should be small, and 2) the time lag should be as short as required (McKenna 1995). The sand pack installation method satisfies both criteria. First, the bentonite chips at the top of the sand pack can isolate the MW's sand pack. The vertical fluid flow along the well axis is thus limited (McKenna 1995). Therefore, the pressure measured in the intake zone is representative of the pressure in the formation. Secondly, the permeable and fairly large intake zone in the traditional installation rapidly equalizes the pressure inequality between the formation and the well thus lessening the time lag (Hvorslev 1951). Under specific circumstances, the fully grouted method can also satisfy the two criteria mentioned above. The hydraulic conductivity of the grout should be low enough to limit the vertical flow along the borehole axis in order to get accurate measurements (McKenna, 1995). Moreover, the specific storage or compressibility of cement-bentonite grout with respect to the compressibility of the surrounding formation (m_{vs}) should be properly designed to avoid having extra time lag.

The principal sources of error for standpipe piezometers have been well documented by Hvorslev (1951). However, for the case of fully grouted pressure transducers, the piezometric error can be related to (1) random and systematic errors due to improper calibration, readings and measurements; (2) systematic error due to incorrect placement of the piezometer; (3) time lag imposed by grout properties; (4) systematic error related to improper sealing; (5) systematic error related to grout hydraulic conductivity McKenna (1995); (5) chemical and thermal induced degradation and evolution of the grout (Smerdon et al. 2014).

This paper concentrates on the analysis of the piezometric error and piezometer response time for fully grouted pressure transducers related to the permeability and stiffness of the cement-bentonite grout. The effect of other sources of error was not assessed in this study.

3 GROUT PROPERTIES

There are several types of commercially available bentonite in North America and elsewhere. They include granulates, powder, chips, and pellets of sodium bentonite. Moreover, calcium bentonite and opalite are also used (Mikkelsen 2002). Bentonite chips or pellets are commonly used to seal the borehole above the sand pack in monitoring wells and stand pipe piezometers. They can also be used to seal the intake zone of a vibrating wire pressure transducer when following traditional (sand pack) procedure for the installation. In the sand pack procedure, the permeability of the seals is low enough to isolate the sand pack. On the other hand, a powder of sodium bentonite is regularly used to produce bentonite slurry or cement-bentonite grout, which backfills the borehole above the chips or pellets in the sand pack method or the entire borehole in the fully grouted method.

There are typically two types of grouts in piezometer installation; bentonite grout and cement-bentonite grout. Bentonite grout is made by mixing water and bentonite powder. The bentonite grouts may be volumetrically unstable, and they are suspected to produce local excess pore water pressure caused by the hydration process. Moreover, it is difficult to pump this kind of grout down the borehole with small diameter tremie pipes (Mikkelsen 2002). By contrast, adding cement into hydrated bentonite results in a much more stable grout which is called self-hardening grout. The mechanical properties of these grouts can be controlled. They are time-dependent, they evolve from a liquid grout to gradually set to become clay-like material (Chapuis et al. 1984). Moreover, adding cement provides the ability to produce a grout mix which is initially less viscous and easier to pump than bentonite grout (Mikkelsen 2002).

As noted earlier, K_g and m_{vg} are key factors in a successful fully grouted transducer installation. The grout permeability is inversely related to the quantity of bentonite (an increased bentonite content lowers the grout permeability). In addition, the grout compressibility also depends on the bentonite-cement ratio. On the other hand, the grout strength depends on the water-cement ratio. It increases by decreasing the water-cement ratio. (Portland Cement association 1984; Contreras et al. 2008; Mikkelsen 2002). Thus, adding more bentonite yields a low permeability and plastic grout (Gustin et al. 2007) for which the time lag might be increased. While adding more cement results in a rigid grout, which may lead in grout cracking during ground movements which would result in macro permeability (McKenna 1995).

One can see that designing and producing a grout with appropriate permeability and compressibility may be the most complicated task in fully grouted installation. Unfortunately, there are not enough data in the literature related to the hydraulic and mechanical properties of cement-bentonite grout mixes. The available data mostly concerns the properties of cement-bentonite mixes that include sand, soil, or other materials for specific geotechnical applications such as cut-off walls, clay liners and so forth. Figure 1 presents some previously published data describing a relationship between unconfined compressive strength (UCS) and cement-water ratio for cement-bentonite grouts.

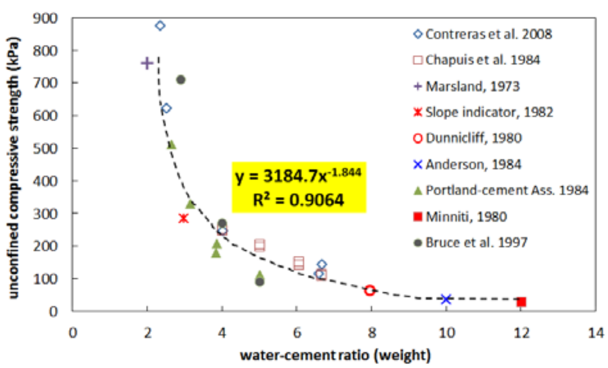

Figure 1. 28-day cement-bentonite UCS versus W/C ratio.

The data in Figure 1 show a relatively good correlation. For a water-cement ratio greater than 2.5, the trended equation (Fig. 1) provides a decent estimate of the cement-bentonite grout strength. It is important to note here that the data with identification of Marsland (1973), Slope indicator (1982), Dunnicliff (1980), Anderson (1984), and Minniti (1980) were directly taken from Mikkelsen (2002).

A review of previous published data of K_g provides some useful preliminary information for users who are interested in using the fully grouted method for pressure transducer installation. Table 1 presents some of published values of K_g for several types of bentonite and cement-bentonite grouts.

The permeability values for fine materials such as intact clays or laboratory-made artificial samples can be predicted based on relationships such as the Kozeny–Carman equation as follows (Chapuis and Aubertin 2003):

$$\log\left(K_{predicted}\right) = 0.5 + \log\left[\frac{e^3}{G_S^2 A^2 (1+e)}\right] \quad [1]$$

where K is in m/s, A is the specific surface area in m^2/kg, G_s and e are specific gravity and void ratio, respectively.

For the case of cement-bentonite grout the void ratio can be calculated as follows (Gustin et al. 2007):

$$e = \frac{V_w}{V_w + V_c + V_b} \quad [2]$$

where V_w, V_c, and V_b are the volume of water, cement, and bentonite which were used in the grout mix, respectively. The specific surface area for the grout mix can be calculated by

$$A = \frac{A_c W_c + A_b W_b}{W_c + W_b} \quad [3]$$

in which A_c and A_b are the specific surface area of cement and bentonite, respectively. The A_c for cement can be assumed 410 m^2/kg (Gustin et al. 2007), while an average value of A_b on the order of 6×10^5 m^2/kg can be considered for bentonite powder (Mesri and Olson 1971). The specific gravity of the grout is given by the weighted average method as follows:

$$G_s = \frac{G_{sc} W_c + G_{sb} W_b}{W_c + W_b} \quad [4]$$

where W_c, W_b, G_{sc}, and G_{sb} are respectively the weight of cement, bentonite, specific gravity of cement and bentonite used in the mix. Average values of 2.95 and 2.75 can be taken for G_{sc} and G_{sb} respectively (Gustin et al. 2007).

Table 1. Published values of K_g (B.S. is bentonite slurry, B.Ch is bentonite chips, and C.B. is the cement bentonite grout).

Grout type	W:C:B	K (cm/s)	Reference
Sodium B.S.	-	10^{-11} to 10^{-12}	Pusch (1992)
B.Ch.	-	1×10^{-9}	Filho (1976)
C.B.	4:01:01	5×10^{-8}	Vaughan (1969)
C.B.	0.2:1:0.03	1×10^{-7}	Chapuis et al. (1984)
C.B.	0.8:1:0.025	1×10^{-8}	McKenna (1995)
C.B.	2.5:1:0.35	1×10^{-6}	Contreras et al. (2008)
C.B.	6.55:1:0.4	6.5×10^{-6}	Contreras et al. (2008)
C.B.	3.99:1:0.67	2×10^{-6}	Contreras et al. (2008)
C.B.	2.0:1:0.36	1×10^{-7}	Contreras et al. (2008)
C.B.	2.49:1:0.41	5×10^{-7}	Contreras et al. (2008)
C.B.	6.64:1:1.19	4×10^{-6}	Contreras et al. (2008)
C.B.	2.66:1:0.27	2×10^{-6}	Contreras et al. (2008)

For some grout properties mentioned in Table 1, K_g was predicted with Eq. (1). For instance, for a grout property similar to that mentioned McKenna (1995), K_g value of 2.83×10^{-8} cm/s was predicted. The predicted and measured values for K_g are in relatively good agreement.

However, the predicted values for the grout properties given by Contreras et al. (2008) were around 1-3 orders of magnitude lower than those measured by these authors. Since in cement bentonite grout part of water reacts away during hydration process of cement, more researches are needed to develop new empirical relationships in order to predict hydraulic conductivity of the cement-bentonite grout.

4 METHODOLOGY

The performance of fully grouted piezometers installed within a clay layer and subjected to a transient flow was investigated using the finite element code SEEP/W, a computer code developed by GEO-SLOPE International. Problems either in a plane or around a vertical axis such as a monitoring well can be solved by this 2D code (Chapuis et al 2001). It solves Darcy's law for seepage and Richards' (1931) equation for mass conservation of water:

$$\vec{\mathbf{V}} = -\mathbf{K}\, grad(h) \qquad [5]$$

$$div(\mathbf{K}\, grad(h)) + Q = \frac{\partial \theta}{\partial t} \qquad [6]$$

where $\boldsymbol{V}$ is the Darcy's velocity vector, $\boldsymbol{K}$ the hydraulic conductivity matrix, h the hydraulic head, Q a local well or source term, θ the volumetric water content and t the time. The final form of Eq. (6) in a vertical plane (z, r) and for transient and saturated follow becomes:

$$k_r\left(\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r}\right) + k_z\frac{\partial^2 h}{\partial z^2} + Q = S_s\frac{\partial h}{\partial t} \qquad [7]$$

where k_r and k_z are the radial and vertical components of the hydraulic conductivity matrix, S_s is the specific storage which is given by the expression $\rho_w g\ (n\beta_w + m_v)$ in which $\rho_w g$ is the unit weight of water, n is the formation porosity, β_w is the compressibility of water taken as 4.6×10^{-7} kPa^{-1} at 20°C, and m_v is the compressibility of the formation.

A horizontal and homogeneous clay layer of constant thickness (3 m) between arbitrary elevations 1 m and -2 m was considered for the numerical axisymmetric model. The fully grouted piezometer was installed in a borehole of radius 5 cm and at the elevation -1.0 m (Figure 2). For comparing the piezometric errors and time lags of different fully grouted piezometers, the case of a perfectly sealed pressure transducer ("ideal piezometer") installed in a sand filter pack using the traditional installation method was also considered. The sand filter in the ideal piezometer was given an m_v value of 4×10^{-8} kPa^{-1} and a saturated hydraulic conductivity $k = 10^{-4}$ m/s. The intake zone of the ideal piezometer had a diameter and height of 10 and 40 cm, respectively. For the ideal piezometer, the borehole above the sand filter was assumed to have been perfectly sealed up to the surface.

The hydraulic head h_i obtained by the ideal piezometer was considered as a reference to assess the error for fully grouted transducers giving a hydraulic head h_{fg}. The normalized error ε at a given time t, induced by the grout properties (K_g and m_{vg}) was expressed as a percentage of the ideal response as follows:

$$\varepsilon = \frac{h_i - h_{fg}}{h_i} \times 100 \qquad [8]$$

Correspondingly, the time lag or the response time of the fully grouted piezometer was compared with the response of the ideal piezometer.

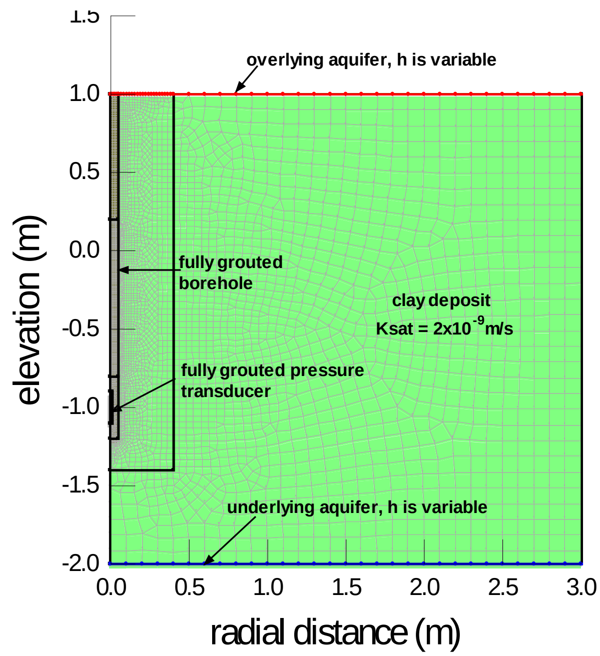

Figure 2. Cross-section of a fully grouted piezometer installed in a clay layer.

Advanced diaphragm type piezometers have a very short response time; they just need a very small volume of water (10^{-3} cm^3) for full scale pressure equalization (McKenna 1995). Therefore, this study simply ignores the time lag induced by the pressure transducer itself. To do so, the piezometers were numerically treated as a perfectly rigid pipe element with radius and length of 1 cm and 15 cm, respectively. A special volumetric water content and hydraulic conductivity for the numerically treated pressure transducer was considered similar to those presented by Chapuis (2009a). The numerically treated transducers have a volumetric water content θ = 90% for u_w > 0 kPa, θ = 10% when u_w < -0.1 kPa, with a linear drop from 90 to 10% when u_w dropped from 0 to -0.1 kPa. The hydraulic conductivity k = 1 m/s for u_w>0 kPa, slowly decreasing to 0.1 m/s and keeping this value for u_w < -0.1 kPa was defined for the transducers. With this special capillary retention curve, the hydraulic head losses within a transducer would be negligible and the transducer is considered very pervious either saturated or not (Chapuis 2009a; Chapuis 2009b).

More than 35 numerical simulations were completed to assess the performance of fully grouted piezometers subjected to transient flow conditions. In the finite element grid, finer elements were used for the piezometer, sand pack, fully grouted borehole, and adjacent clay to ease interpolation, and simplify convergence. Moreover, with the finite element method, solutions must be independent of the mesh size (Chapuis 2009a; 2009b, 2010). The finer element sizes were 5 mm in the piezometers and 10 cm in clay layer far away from the borehole. Figure 3 presents the detailed mesh used around the fully grouted piezometer. For the 3-m thick clay layer and for the assumed hydraulic head boundary conditions, Chapuis (2009a) noted that the hydraulic head fluctuations around the borehole was negligible at radial distances r > 1 m and thus the grid extent was limited to a maximum radial distance of 3.0 m. The final simulations were conducted with meshes that comprised 6078 nodes and 6049 elements.

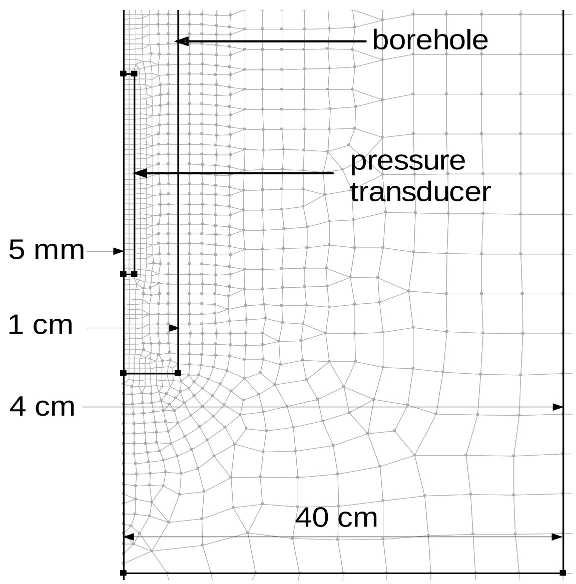

Figure 3.Refined mesh around the piezometer

The numerical simulations were carried out in two steps. The first step was to model a steady state condition which was used as an initial condition for transient flow. The steady state step was initiated with applying an arbitrary constant total head boundary condition of 0.0 m and 1.0 m at the bottom and the top boundary of the clay layer, respectively. The second step was to model a transient flow condition. To do so, hydraulic head versus time *H(t)* boundary conditions were applied at the upper and lower layers of the clay layer. In this study the transient flow condition was simply initiated by quick (1-day) change of hydraulic head in the lower and upper aquifers. The hydraulic head boundary conditions were linearly increased (in 1-day) from 1.0 m to 1.9 m at the upper boundary and from 0.0 m to 1.0 m at the bottom boundary.

Seep/W implicitly assumes constant total stresses in the solution of seepage problem. Therefore, the pore water pressure measured with the ideal piezometer depends on the fluctuations of the hydraulic head at the upper and lower boundary of clay layer. For the case of fully grouted piezometer, it also depends upon the grout characteristics such as K_g, and m_{vg}. The numerical model in this study assumes an overconsolidated clay similar to soft Champlain clay with a single value for the hydraulic conductivity ($K_c = 2\times10^{-9}$ m/s) and for compressibility ($m_{vc} = 2\times10^{-5}$ kPa^{-1}). However, various grout characteristics were considered in order to investigate the impact of grout properties on pore pressure measurement. Thus, the K_g values were varied between 2×10^{-6} and 2×10^{-12} m/s based on values reported in the literature. The m_{vg} values were varied between 2×10^{-3} and 2×10^{-7} kPa^{-1}. Hence, with this numerical study one can examine the error and time lag induced by the grout properties (various hydraulic conductivity and compressibility) with respect to the characteristics of the surrounding clay.

5 RESULT AND DISCUSSION

The parameters have been defined as dimensionless numbers in order to compare their influence on the piezometric error that arises from different K_g, and m_{vg} values for the cement-bentonite grout. The dimensionless parameters are the permeability ratio (K_g/K_c) and the compressibility ratio (m_{vg}/m_{vc}). The range of dimensionless parameters for this numerical study was 10^{-3} to 10^3 for K_g/K_c and 10^{-2} to 10^2 for m_{vg}/m_{vc}.

For a fully grouted piezometer with a compressibility value similar to adjacent clay ($m_{vg}/m_{vc} = 1$), the impact of grout permeability on hydraulic head equalization is presented on Figure 4.

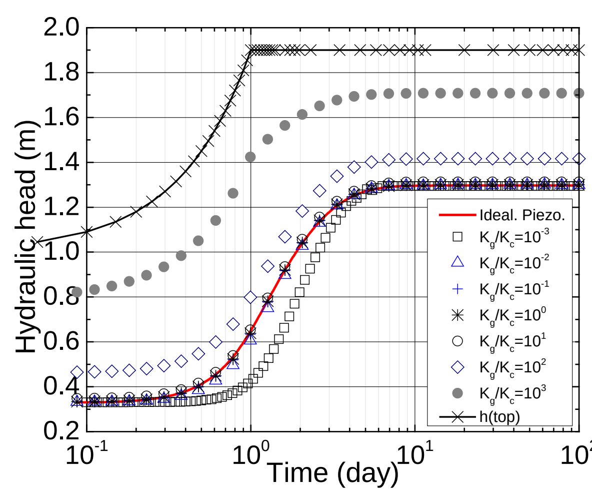

Figure 4. Hydraulic head response of fully grouted transducer as a function of K_g/K_c for $m_{vg}/m_{vc} = 1$.

For the grout with a permeability ratio of 10^{-3}, the piezometer response was delayed. While, for a ratio K_g/K_c between 10^{-2} and 10^1, the fully grouted transducer shows very good hydraulic head response with respect to the ideal transducer. On the other hand, for $K_g/K_c \geq 100$ fully grouted piezometers measured hydraulic heads higher than those recorded with the ideal piezometer. As shown on Figure 4 for $K_g/K_c = 10^3$, the hydraulic head registered with the fully grouted transducer was close to the hydraulic head of the upper aquifer. This indicates that with a high permeability grout, a hydraulic short-circuit might be established between the transducer and upper aquifer (Marefat et al. 2014).

Our numerical results indicate that the response of fully grouted transducers also depends upon the compressibility ratio (not shown here). For instance, when a ratio $K_g/K_c = 1$ was considered for numerical analysis, for a compressibility ratios between 10^{-2} and 10, the fully grouted transducer provided a very good hydraulic head measurement with respect to ideal piezometer. However, when the borehole was backfilled with a grout softer than the adjacent clay ($m_{vg}/m_{vc} > 10^1$), the hydraulic head recorded by the fully grouted pressure transducer was delayed compared to the ideal piezometer.

5.1. Error versus permeability ratio (K_g/K_c)

The piezometric error was calculated with Eq. (8). Based on Eq. (8), negative ε values are associated with grouts with $K_g/K_c > 1$. In the ideal piezometer, 95 % of pore pressure imbalance was equilibrated after 4.27 days. The hydraulic heads corresponding to 95 % of pressure equalization for both ideal and fully grouted transducers was considered to calculate the piezometeric error. For each m_{vg}/m_{vc} ratio, the piezometeric error versus permeability ratios is presented on Figure 5.

For a given m_{vg}/m_{vc} ratio the piezometric error depends upon the permeability ratio. For a grout with a compressibility value similar to or lower than that of the adjacent clay ($m_{vg}/m_{vc} \leq 1$), ε was negligible for $K_g/K_c \leq 10$. However, the error became significant when a high permeability grout ($K_g/K_c > 10$) was considered for the borehole. On the other hand, for a grout softer than the adjacent clay ($m_{vg}/m_{vc} > 1$), the error was significant even for the low permeability ratios ($K_g/K_c = 10^{-2}$ and 10^{-3}). Nevertheless, the error was insignificant for a permeability ratio between 10^{-1} and 10. Similarly, it was increased with increasing permeability contrast between grout and adjacent soil ($K_g/K_c > 10$). As shown on Figure 5, for $K_g/K_c > 10$ the grout compressibility has no significant influence on the error. The error is mostly controlled by the permeability ratio. However, if the grout is more impervious than the surrounding clay, the grout should be stiffer than the clay to obtain representative measurements.

Our numerical results for transient flow conditions imply that the previous finding of Vaughan (1969) and Contreras et al. (2008) might be true just under certain circumstances. As shown on Figure 5, there is around 10 percent error for a fully grouted transducer with grout permeability up to two orders of magnitude greater than clay permeability. The error can be also higher if there is a higher vertical hydraulic gradient through the clay layer. This was proven analytically and numerically by Marefat et al. (2014) for steady state seepage. For the transient flow condition considered in this study, the numerical results confirm the claim by Marefat et al. (2014) that the K_g/K_c ratio should be lower than 10 to obtain reliable measurements with fully grouted transducers for most field conditions. For the problem studied in this paper, with a vertical hydraulic gradient of around 0.3, the fully grouted transducer has to satisfy a permeability ratio of $10^{-1} \leq K_g/K_c \leq 10$ to yield representative data with respect to the ideal piezometer.

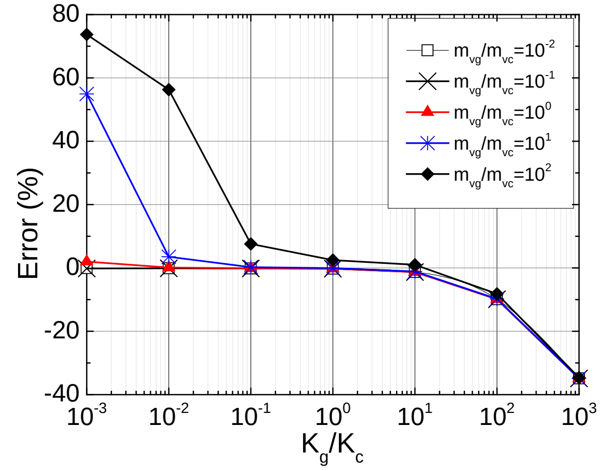

Figure 5. Error versus K_g/K_c as a function of m_{vg}/m_{vc}.

5.2. Error versus compressibility ratio (m_{vg}/m_{vc})

The piezometric error versus compressibility ratio for different combinations of K_g/K_c is presented on Figure 6. It is clearly shown that m_{vg}/m_{vs} has no significant influence on the error for grouts with $K_g/K_c \geq 10^{-1}$. However, for a grout that is much less pervious than the adjacent formation ($K_g/K_c < 10^{-1}$), the error depends upon m_{vg}/m_{vc}. From Figure 6, one can conclude that the grout compressibility is important if the grout permeability is much lower than the adjacent soil permeability. However, for high permeability grout ($K_g/K_c = 10^2$ and 10^3) the piezometric error was constant with respect to compressibility ratio, and also significant (around 10 % and 35% for $K_g/K_c = 10^2$ and 10^3, respectively). However, for K_g/K_c between 10^{-1} and 10, the error was negligible for all values of m_{vg}/m_{vc} which were considered in these numerical simulations.

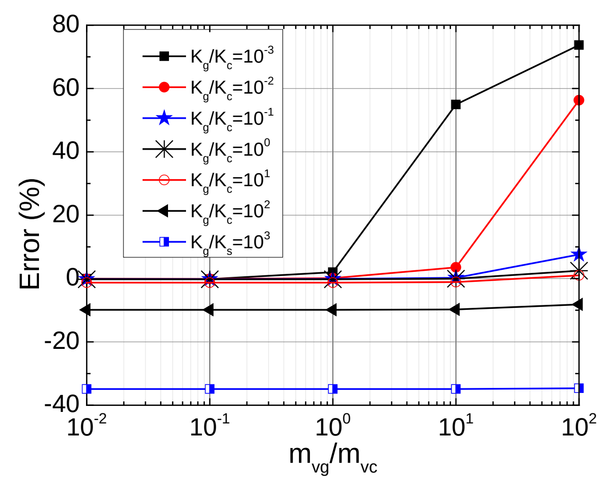

Figure 6. Error versus m_{vg}/m_{vc} as a function of K_g/K_c.

5.3. Error versus pressure response time

The pore pressure response versus time for a fully grouted transducer was compared with that for the ideal transducer. It was calculated and presented as a percentage of the ideal pore pressure response based on Eq. (8) for various combinations of the m_{vg}/m_{vc} and K_g/K_c ratios. Figure 7 presents the error with respect to time for fully grouted transducers as a function of K_g/K_c for $m_{vg}/m_{vc} = 1$. Firstly, for a permeability ratio of 10^3, the fully grouted transducer did not provide representative measurement. For a permeability contrast of 10^2, the fully grouted piezometer initially shows a 40% percent error which is decreased to around 10% through time (after around 4 days). As mentioned in section 5.1, the time equal to 4.27 days is related to 95% present of the pore pressure imbalance for the ideal piezometer. Therefore, this time was taken as a base time to compare the error versus time for the fully grouted piezometer in this study.

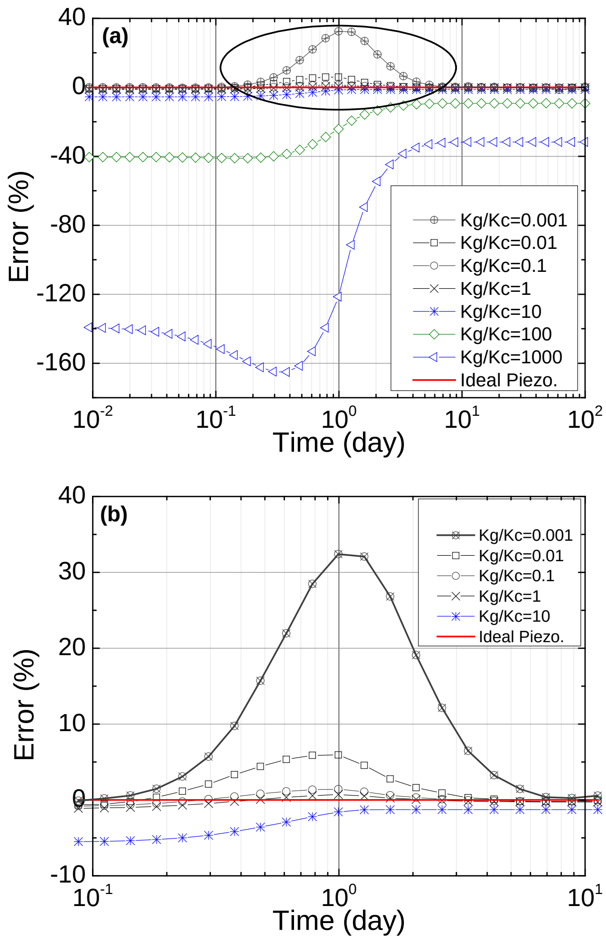

Figure 7. Error versus time as a function of K_g/K_c: a) for $m_{vg}/m_{vc} = 1$, b) enlarged part of graph a.

For $10^{-3} \le K_g/K_c \le 10$, the error between 0.1 and 10 days is enlarged on Figure 7b. As shown, for K_g/K_c values of 10^{-2} and 1 the hydraulic head measured with a fully grouted piezometer was roughly similar to that recorded by the ideal piezometer. For $K_g/K_c = 10^{-3}$, the hydraulic head response was initially delayed; the error decreased after around 4 days and became less than 2%. For $K_g/K_c = 10$, the error after 1 day became constant and negligible. From figure 7b one can conclude that, for a grout as rigid as the surrounding soil with a permeability ratio of $10^{-2} \le K_g/K_c \le 10$, a fully grouted transducer provided acceptable hydraulic head measurements.

Figure 8 presents the error versus time as a function of m_{vg}/m_{vc} for permeability ratios of 10^{-3} and 1. From Figure 8a it is clear how the grout compressibility affects the piezometer response and the error. For example, with $m_{vg}/m_{vc} = 10$ and $K_g/K_c = 0.001$, the error became negligible after around 11 days (Figure 8a). However, a grout with $m_{vg}/m_{vc} = 1$ and $K_g/K_c = 0.001$ provided similar hydraulic head measurement after around 4 days. Moreover, for an m_{vg}/m_{vc} value of 100, the response of the fully grouted piezometer was totally delayed.

The error versus time for a grout with $K_g/K_c = 1$ is presented on Figure 8b. For this permeability ratio the fully grouted method provided representative hydraulic head response for all range of m_{vg}/m_{vc} considered in this study. However, for $m_{vg}/m_{vc} = 100$ the piezometer response was delayed initially, the error became negligible after 4 days.

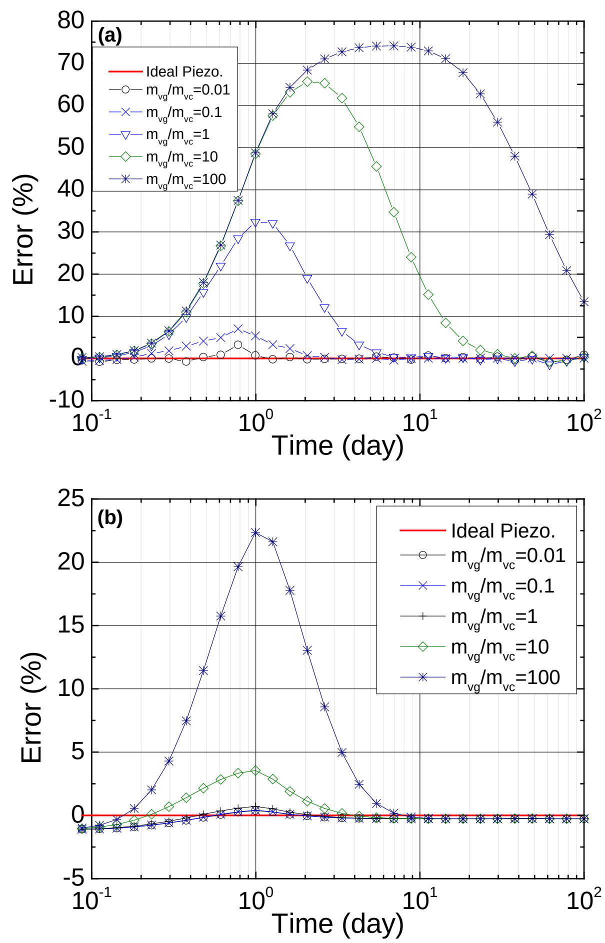

Figure 8. Error versus time as a function of m_{vg}/m_{vc}: a) for $K_g/K_c = 0.001$, b) for $K_g/K_c = 1$.

6 CONCLUSION

The fully grouted technique to install piezometers has many advantages such as reduced cost, ease of installation, no risk of failure for the sand pack of deeper wells, and share single borehole with various instruments. In this paper, numerical models have been developped to investigate the performance of fully grouted piezometers subjected to transient flow conditions. For a single transient flow considered in this paper, the results indicate that the error magnitude is strongly related to the permeability ratio. It also depends upon the grout compressibility. The numerical results showed that the permeability contrast between grout and surrounding clay can be between 10^{-1} and 10 without producing a significant piezometric error. For $K_g/K_c < 10^{-1}$, the grout should be stiffer than the adjacent soil in order to have a shorter time lag.

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