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Applicability of the fully grouted piezometer installation method for transient seepage conditions

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ABSTRACT
The use of the fully grouted method (FGM) to install and backfill vibrating wire piezometers has been growing in popularity. Published modelling results from finite element seepage analyses under steady state conditions show the range of grout/soil permeability ratios under which the FGM is considered reliable. There is limited published literature with comparisons between the results of field installations using the FGM and the traditional sandpack with bentonite chip seal method. The earlier published data that formed the basis for widespread adoption of the FGM did not consider situations where transient porewater pressures resulting from application of external stresses (e.g. embankment construction) are induced in a low permeability layer, and there are a range of soil and transient seepage conditions under which the fully grouted installation method may not provide reliable results. This paper reports the results of transient finite element analyses of fully grouted installations in low permeability clay layers where there are adjacent higher permeability soil layers, and provides additional insight into the applicability and limitations of the FGM. The results of several parallel installations using the FGM and the traditional sandpack with bentonite chip seal method are also reported to provide empirical reference cases.

RÉSUMÉ
L'utilisation de la Méthode entièrement injecté (MEI) avec coulis de ciment pour l'installation des piézomètres à corde vibrante a gagné en popularité. Plusieurs articles appuyés par des résultats de modélisation par éléments finis d'analyses d'écoulement qui assume des conditions en régime permanent présentent la plage de rapports de perméabilité coulis / sol dans laquelle la MEI est considérée comme fiable. Peu d'articles ont été publiés comparant à l'aide de données de terrain la MEI et la méthode traditionnelle d'installation qui emploie une lanterne de sable et des bouchons de bentonite. Les données initialement publiées, qui ont conduit à l'adoption répandue de la MEI, ne tenaient pas compte des situations dans lesquelles des pressions interstitielles transitoires provenant de l'application de contraintes externes (c.-à-d. la construction d'une digue) sont induites dans une couche à faible perméabilité. Il existe des sols et des conditions d'écoulement transitoires pour lesquelles la MEI ne pourrait pas fournir des résultats fiables. Cet article présente des résultats d'analyses par éléments finis lorsque la MEI est utilisée en régime transitoire dans des couches d'argile à faible perméabilité adjacentes à des couches de sol de perméabilité supérieure. L'article précise certaines conditions d'applicabilité et limites de la MEI. Les résultats de plusieurs installations parallèles utilisant la MEI et la méthode d'installation traditionnelle sont également inclus comme cas de référence empiriques.

1 INTRODUCTION

The use of the fully grouted method (FGM) to install and backfill vibrating wire piezometers (VWPs) has been growing in popularity. Studies have been published with modelling results from finite element seepage analyses under steady state conditions, showing the range of grout/soil permeability ratios under which the fully grouted installation method is considered reliable. There is limited published literature with comparisons between the results of field installations using the fully grouted method and the traditional sandpack with bentonite chip seal method. The earlier published data that formed the basis for widespread adoption of the method did not consider situations where transient porewater pressures resulting from application of external stresses (e.g. embankment construction) are induced in a low permeability layer, and there are a range of soil and transient seepage conditions under which the fully grouted installation method may not provide reliable results.

2 BACKGROUND

2.1 Piezometer installation methods

The conventional piezometer installation method uses a sandpack surrounding the piezometer tip, and a bentonite chip or pellet seal above (and below, if the piezometer is not at the bottom of the borehole). Good practice is to have the length of the sandpack as short as practical, and for it to be fully sealed in and distant from the upper and lower boundaries of the soil layer where the pore pressure is being measured. The bentonite seal should be at least several metres long to limit vertical flow between the sandpack and adjacent higher permeability soil layers. A maximum of two piezometers are placed in one borehole, to prevent leakage around the cables through the bentonite seals. The remainder of the borehole above the bentonite seal may be grouted with a cement-bentonite grout. An example of a sandpack installation is shown on Figure 1.

The FGM of installing VWPs omits the sandpack and bentonite chip seal, and uses a carefully proportioned and mixed cement-bentonite grout to seal the entire borehole, including directly around the piezometer tip. Because

VWPs require extremely small changes in pore water volume to deflect the measuring membrane, the piezometers respond quickly to changes in formation pore pressure despite the low permeability of the grout. The FGM is faster and somewhat easier to install than the conventional sandpack and chip seal method. More details are provided in the literature review section of this paper.

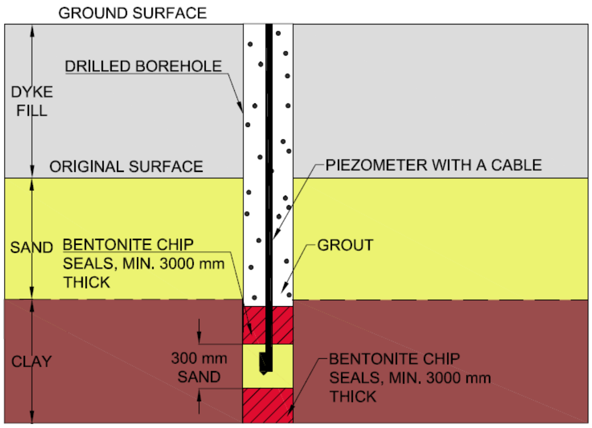

Figure 1. Sandpack piezometer installation to limit piezometric errors

2.2 Terminology

In this paper, high and low permeability soils will be generically referred to as sand and clay.

2.3 Potential errors with partially sealed boreholes

A well or sandpack piezometer will read the pressure in the most permeable unit that the screen or sandpack is in contact with. This can be validated conceptually; consider a situation with two soil layers, one sand and one clay, and the clay has a higher hydraulic head than the sand. An open well is screened across both layers. Water from the clay will seep into the well and would increase the water level in the well, however, water will flow out of the well into the sand at a much greater rate than the water from the clay can flow in, and so the water level in the well will be controlled by the sand layer. This concept can then be extended to a fully grouted piezometer. If the permeability of the grout is much greater than the clay layer, water will flow along the grouted borehole and again the piezometer will measure, or at minimum be influenced by, the water level in the adjacent sand layer.

When an embankment is constructed, there is an increase in the total and shear stresses in the foundation. This results in an increase in the pore pressure in the foundation soils. For a sand layer, this increase in the pore pressure may dissipate so quickly that it is not observed. In an adjacent clay layer, however, the dissipation will be slow, and hence the hydraulic head in the clay will be higher than that in the sand. If a piezometer is installed to measure the porewater pressure in the clay layer but the backfill in the borehole allows communication of pressure from the location of the piezometer to the sand layer, the piezometer will always under-read the true pressure since the transient seepage is from the clay to the sand, and will give a misleading indication that the pore pressure is lower, and stability of the structure is greater than it really is. For this application, the error is always unconservative.

3 LITERATURE REVIEW

This section reviews the papers most commonly referenced in support of the fully grouted method, as well as some more recent research that examined a broader set of soil and seepage conditions.

Vaughan (1969) used analytical solutions to examine the case of a piezometer installed in a grouted borehole that is drilled through an impermeable material into an underlying permeable layer, with the piezometer installed in the lower layer, under conditions of steady state flow with an implied zero pressure boundary condition at the ground surface, and flow along the borehole grout plug to the location of the piezometer tip. A second scenario was examined with a piezometer sealed in a homogeneous material. The flow to the borehole plug was radial, and no-flow or zero pressure boundary conditions were assumed for the top of the borehole at the ground surface.

On the basis of the analyses of these simplified conditions, Vaughan concluded “In certain configurations, the permeability of the grout plug can be several orders of magnitude greater than the soil without significant error resulting.” The author did not consider a case where the piezometer was installed in a low permeability soil layer with the borehole penetrating a higher permeability layer.

McKenna (1995) described both the theoretical and practical applications of fully grouted piezometers and gave examples of field results from several installations in systems of layered stratigraphy with complex groundwater conditions. McKenna demonstrated that the hydrodynamic time lag is typically small, and so the grouted piezometer can be expected to respond quickly to changes in the groundwater pressure in the soil adjacent to the borehole. McKenna noted that “if any hydraulic gradients exist between layers penetrated by the borehole and the grout is more permeable than the formation, large errors can result and these errors are difficult to predict.” McKenna concluded "In general, all seals for all piezometer types must be less permeable than the formations intersected by the borehole."

Mikkelsen (2002) described the properties and recommended mixing methods for cement-bentonite grouts, focusing on the permeability of these grouts for application to sealing piezometers in boreholes, and provided mix designs for hard and soft soils that have been commonly accepted in geotechnical practice.

Mikkelsen and Green (2003) advocated that “traditional (borehole sealing) methods should be abandoned and that pneumatic and vibrating wire diaphragm piezometers can be more simply installed directly surrounding them with cement-bentonite grout in the borehole. The method is not only easier and faster, but has a much better chance of succeeding in measuring the correct ground water pressure.” The evidence used by Mikkelsen and Green to support the latter statement is based on the work of

Vaughan (1969), and the authors do not consider any installation scenarios beyond the steady-state, simple stratigraphy considered by Vaughan. Mikkelsen and Green, later repeated by Contreras et al. (2007, 2012), state “Use of a higher permeability borehole seal is possible because of the much higher horizontal hydraulic gradients adjacent to the piezometer than the vertical gradients along the grouted borehole.” However, these conditions would cause the opposite effect, since a large horizontal gradient between the formation and the borehole results in a large head difference between the formation and the piezometer, and therefore a large error.

Contreras et al. (2007, 2008) investigated the grout permeability requirements for the FGM using a finite element model, and recommended that the borehole grout can be up to three orders of magnitude more permeable than the formation for which the measurements are desired. In the finite element model used by Contreras et al. (2007, 2008) a sand layer was modelled below a clay layer with a gradient under steady state conditions, but the borehole did not penetrate the interface between the clay and sand layers, and therefore cannot serve as a conduit for seepage between these layers. The model results are therefore only valid for specific scenarios.

Contreras et al. (2012) reported comparisons between field installations using open standpipes and the vibrating wire piezometers using the FGM. The authors report small normalized errors for field piezometer readings which appear to support the results reported by Contreras et al. (2007, 2008). However, the magnitude of the normalized error is a function of the datum used for the hydraulic head. In the case reported, a large datum was chosen and an error of several metres that may be practically significant would still show as a very small normalized error.

Li (2012) performed numerical simulations and found that under steady state conditions, the errors were small for a permeability ratio of up to 100 times. Li also examined a transient loading case and concluded that a permeability ratio of 100 would result in small errors. However, the author assessed the results at locations 4 m and 12 m from the clay-sand interface. As discussed in Section 4, larger errors occur closer to the interface.

Marefat et al. (2014, 2015, 2017 and 2018) present a more thorough consideration of the conditions under which full grouted piezometers are reliable. Marefat et al. (2014) examined the case of a grouted borehole with a piezometer that penetrates both sand and clay layers under a steady-state vertical gradient. Under these conditions, a high permeability grout creates a flow pathway or hydraulic short-circuit, and potentially large errors in the piezometric reading compared to the surrounding ground. The authors identified the grout permeability, the grouted borehole length, and the hydraulic gradient in the clay layer as key contributors to the piezometric error. The authors also concluded that the previous findings by Vaughan (1969) and Contreras et al. (2007, 2008, 2012) that the grout permeability could be several orders of magnitude higher than the soil, might only be true when the vertical hydraulic gradient is very low in the layers penetrated by the borehole. All other factors being equal, the error was proportional to the vertical hydraulic gradient. The authors concluded that for most field conditions, with a vertical gradient less than 1, the grout permeability could be greater than the surrounding formation by a factor of 10. Marefat et al. (2015) reported the results of numerical models that examined the influence of both the grout/soil stiffness and permeability ratios. The authors demonstrated that errors can also result if the grout is much less permeable than the formation, unless the grout stiffness is similar or stiffer than the formation.

Marefat et al. (2017) described the field performance of fully grouted piezometers installed in a layered stratigraphy. The authors noted that “preparing an appropriate grout is less trivial than it might seem when fully grouted piezometers are planned to monitor a formation with a very low permeability” and found that when a permeability ratio of 200 between the grout and the formation was used, the pore pressures differed greatly as compared to those when the permeability of the grout more closely matched the formation.

Marefat et al. (2018) used numerical modelling to examine the response of a grouted piezometer in a clay layer to transient changes in the water pressure in adjacent aquifers, and found that the results were sensitive to the grout permeability and the soil compressibility (for a constant soil permeability), and insensitive to the grout compressibility. They also modelled the transient response to an external surface load applied on the soil surface over a discrete circular area, and found that the results were most sensitive to the grout permeability at shallow depths where the induced pore pressures and gradients were highest. The authors also examined field data with parallel piezometer installations and found that pore pressures in a grout with 1000 times higher permeability than the formation resulted in measured pore water pressures “totally different” from those obtained with a low permeability grout. From the transient modelling and field observations, the authors concluded that a permeability ratio of 100 was the upper limit to obtain acceptable porewater pressure readings. They cautioned that stiff grouts are vulnerable to cracking if there is ground deformation, resulting in hydraulic short-circuits.

4 TRANSIENT MODEL ANALYSIS

4.1 Model Description

To investigate the range of grout permeability where the FGM would provide a reliable indication of formation pore pressure, an axi-symmetric finite element model was created using the Geostudio Seep/W v2016 software. The model comprised a two-layer system: 10 m of sand overlying 10 m of clay, with the borehole fully penetrating both layers. This is a key difference from the model by Contreras et al. (2008) where the sand layer was below the clay layer and the borehole terminated in the clay layer without crossing the boundary into the sand layer.

In this current model, the groundwater table was assumed at the ground surface (0 m elevation) with a hydrostatic pressure distribution (head set to 0 m). The effect of an external load corresponding to a rapid placement of 5 m of construction backfill (bulk density 2000 kg/m^3) was simulated by setting the initial head in the clay layer to 10 m. This presumes that the permeability of the sand layer was sufficiently high that any excess porewater pressure due to the external load immediately dissipates, while the porewater pressure in the clay layer responded to the full change in vertical stress from the fill placement (instantaneous $\overline{B}$ = 1.0). The application of external stress was modelled as occurring over a large lateral extent, so that in the absence of the borehole, seepage due to dissipation of the excess pore pressure would be one-dimensional vertically. The bottom boundary condition was set to no-flow so that the consolidation system was single-drained, though the results of the model could easily be extended to a double-drained scenario.

These conditions replicate a common scenario in embankment dam construction. Under this transient loading condition, a very high gradient exists between the clay and sand layers, and based on the observations of Marefat et al. (2014) a high error in the piezometer reading would be expected if the grout permeability is high relative to the clay.

Once these initial conditions were established, a transient analysis was run for a period of 5 years.

The head was monitored as a function of time at several locations in the grouted borehole and in the far-field clay (15 m distance from the borehole was found to be sufficient to have negligible influence from the borehole). The hydraulic head was monitored (piezometer locations) at depths of 1, 2, 5, and 10 m below the sand-clay interface. The finite element mesh, the initial state boundary conditions and the head monitoring locations (blue dots) are shown on Figure 2.

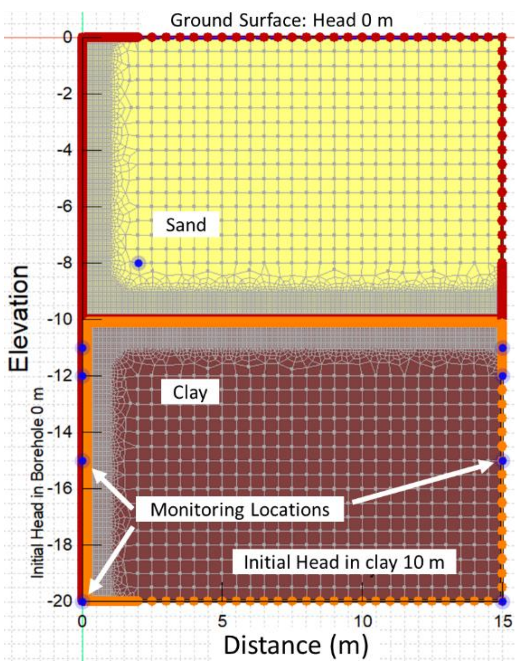

Figure 2. Finite element mesh with initial boundary conditions and monitoring locations

The material parameters used in the model are listed in Table 1. The base case parameters are denoted with an asterisk. Analyses with the base case parameters were performed for a range of grout permeability from $1x10^{-5}$ m/s (equal to the sand) to $1x10^{-10}$ m/s (equal to the clay). Sensitivity analyses were performed over a partial range of grout permeability to examine the effects of varying the sand permeability, the clay stiffness and the grout stiffness. Isotropic permeability was assumed for all materials.

One further set of sensitivity analyses was performed assuming that rather than the initial head in the grout being equal to the clay layer, the initial head in the grout was equal to the sand layer. This could represent the situation where the borehole was drilled after the external load was applied.

Table 1. Material parameters

Material	K (m/s)	m_v (kPa^{-1})	n
Sand*	$1x10^{-5}$	$2x10^{-5}$	0.4
Sand - silty	$1x10^{-7}$ to $1x10^{-8}$	$2x10^{-5}$	0.4
Clay – soft*	$1x10^{-10}$	$5x10^{-5}$	0.4
Clay – hard	$1x10^{-10}$	$1x10^{-5}$	0.35
Grout – soft*	$1x10^{-5}$ to $1x10^{-10}$	$1x10^{-4}$	0.4
Grout - hard	$1x10^{-8}$ to $1x10^{-9}$	$1x10^{-5}$	0.4

*base case parameters

4.2 Analysis Results

Following application of the external load, the pore pressures (and hydraulic head) are initially much higher in the clay than the sand. This results in upward seepage in the clay, and dissipation of the excess pore pressures towards the sand-clay interface. If the permeability of the grout in the borehole is greater than the clay, then the dissipation of excess head in the borehole will occur more rapidly.

The analysis results demonstrate that in order to obtain accurate porewater pressure measurements under transient seepage conditions, the permeability of the grout cannot be substantially higher than that of the soil. This is consistent with the findings of Marefat et al. (2018) who found that the larger permeability ratios noted by earlier researchers are valid only for low vertical gradients. In the case of this present analysis, the vertical gradients near the sand/clay interface are very high. This is shown on Figure 3 for the case where the grout permeability is $1x10^{-7}$ m/s. The head in the clay is shown with blue symbols and lines, and black for the grout. The head is shown for at four depths below the clay-sand interface, with the same symbol used to compare the grout and clay head at each depth. Additionally, the head (0 m) in the sand is shown for comparison. At small times after application of the load, the head is the same in the grout and clay at all depths. At shallow depths below the interface (D=1 m), dissipation in the grout is evident at 0.01 days, compared to about 5 days in the clay. The largest error is at shallow depths below the interface, and can be read from the vertical axis of the graph by comparing the same symbol shape for the grout and clay curves. The largest error is about 7 m (70% of the initial excess head) and occurs within the first week. As the system moves toward steady state, the error decreases, but the error is still more than 1 m (10% of the initial excess head) for 1 year.

The implication of this error is that if a FGM piezometer is being used to monitor the stability of an embankment for potential shear failure in a weak clay layer near the interface, for a permeability ratio of 1000, the piezometer would significantly under-report the actual pore pressure during the time period where the engineers may be considering if enough dissipation has occurred to permit placement of the next lift of embankment fill.

In contrast to the large errors evident with a permeability ratio of 1000, the results for a permeability ratio of 10 (grout K=1x10^{-9} m/s) are shown on Figure 4. In this case, the maximum piezometric error is about 0.5 m at shallow depth in the clay, and occurs within about the first month after application of the load.

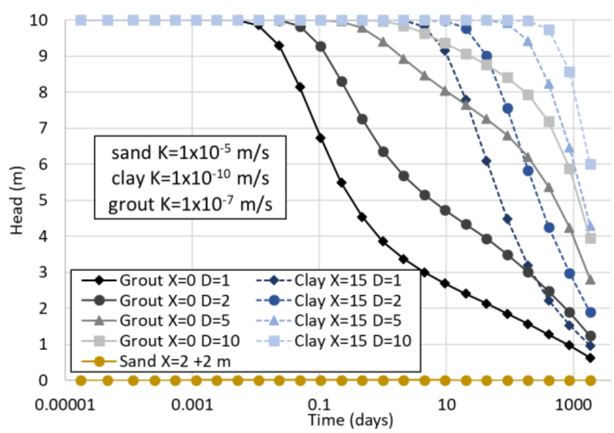

Figure 3. Hydraulic head vs. time in the borehole and far-field clay, base case parameters, grout K=1x10^{-7} m/s

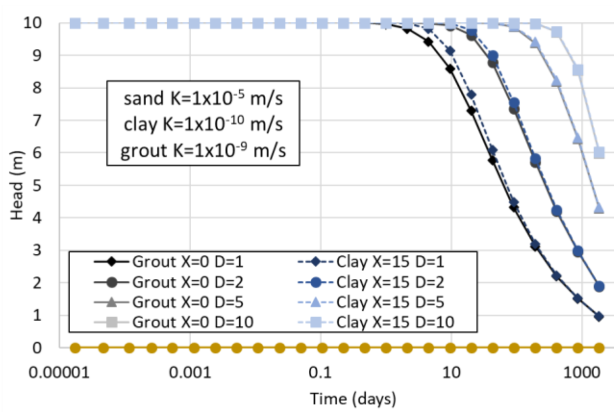

Figure 4. Hydraulic head vs. time in the borehole and far-field clay, base case parameters, grout K=1x10^{-9} m/s

The relationship between piezometric error and grout permeability can also be seen in Figure 5 (grout K = 1x10^{-7} m/s) and Figure 6 (grout K = 1x10^{-9} m/s), which compare the head along two vertical profiles: through the grouted borehole, and through the far-field clay, at times of approximately 1 week, 1 month and 1 year. In these graphs, the error is the difference along the horizontal axis (at the same elevation) between the grout and clay curves with same symbol (same time).

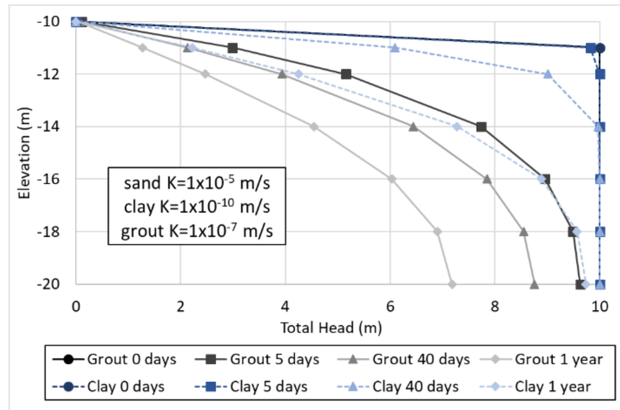

Figure 5. Comparison of head at several times, along vertical profiles through the grouted borehole and far-field clay, grout K=1x10^{-7} m/s

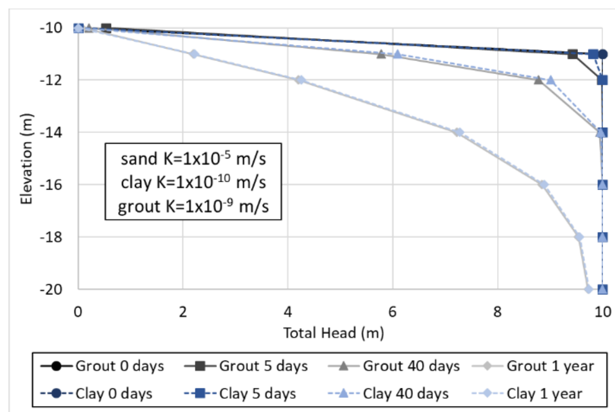

Figure 6. Comparison of head at several times, along vertical profiles through the grouted borehole and far-field clay, grout K=1x10^{-9} m/s

Figure 7 summarizes the results across the range of grout permeability modelled, from 1x10^{-5} m/s to 1x10^{-10} m/s (permeability ratios ranging from 100,000 to 1), at two times: approximately 3 weeks and 1 year after application of the load. At 3 weeks (solid lines), the errors can be meaningfully large for permeability ratios greater than 10. After 1 year (dashed lines), a permeability ratio of 100 would result in only minor errors. In the short term, the errors are largest at shallow depths (1 m, triangles) though at longer times, the deeper piezometers (5 m, circles) have larger errors. This is because by one year, the excess pore pressure in the clay near the interface has significantly dissipated and hence the remaining absolute error between the piezometer in the grout and the pressure in the clay is small, whereas at greater distances from the sand-clay interface, more excess pore pressure remains in the clay while the pressure in the grout continues to be affected by vertical flow towards the sand layer.

The model was run with two different initial conditions in the borehole: H=0 m (equivalent to the head in the sand) and H=10 m (equivalent to the head in the clay following application of the external load). Previous authors noted that a grouted piezometer will respond quickly to changes in pore pressure in the formation near the borehole (short hydrodynamic time lag). This was validated by the transient model, as the assumption of the initial head in the borehole did not affect the results beyond the first few days from the application of the load; the pore pressures in the borehole were essentially the same regardless of which initial condition was used for the head in the borehole.

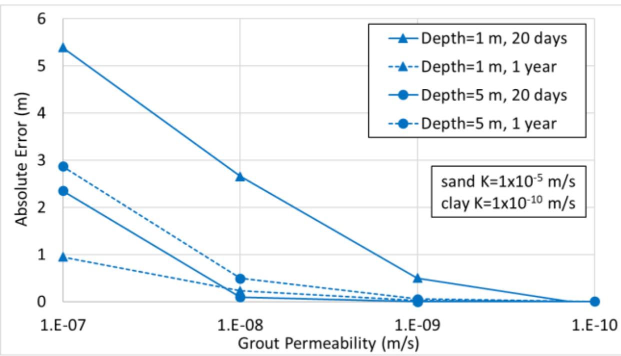

Figure 7. Summary of absolute piezometer error for a range of grout permeability, initial borehole head conditions, depths and times

In addition to the baseline clay stiffness (m_v=5x10^{-5} kPa^{-1}, E=20 MPa), sensitivity analyses were run with a hard clay (m_v=1x10^{-5} kPa^{-1}, E=100 MPa). The stiffness of the clay affected the magnitude of the piezometer error with stiffer clays having a lower piezometer error, all other factors being equal. This is because both the clay permeability and stiffness are factors in the coefficient of consolidation; for conditions where the transient seepage is driven by consolidation, increasing the stiffness of the clay has the equivalent effect of increasing the permeability of the clay, and hence reducing the permeability contrast with the grout. This can be seen in Figure 8. The stiffness of the grout was found to have less influence on the error, for the scenarios that were modelled.

In all cases, because the induced head in the clay was higher than in the sand, the influence of a hydraulic connection in the borehole was to reduce the head in the grout compared to the surrounding clay. The piezometer error was therefore to always under-read the pore pressure compared to the adjacent clay.

Lowering the permeability of the sand from 1x10^{-5} m/s to 1x10^{-8} m/s did not have a substantial effect on the errors. The controlling factor was the relative difference between the grout and clay permeability, not the grout and sand permeability.

Where the grout permeability is substantially higher than the clay, the grout acts like a wick drain, so that the direction of flow as the excess pore pressures in the clay dissipate are both upward to the clay/sand interface and horizontally towards the borehole. This can be seen in Figure 9, which uses a uniform 10 m excess initial head in both the clay and the grout. It is evident that the head in the grout column, although initially identical to the clay, quickly reduces due to the high flows in the grout upward towards the interface with the sand layer. At one year following application of the load and excess pore pressure in the clay, there is still approximately a 3 m error between the head in the borehole at this depth, and the head in the clay. This error will gradually reduce as the flow system moves towards steady state and the gradients decrease.

In situations where there is a large vertical gradient between layers of contrasting permeability in the soil formation, to accurately read the pressure in the low permeability layer it would be necessary to have a high gradient (seal) in the borehole and low gradient horizontally between the piezometer and the adjacent soil.

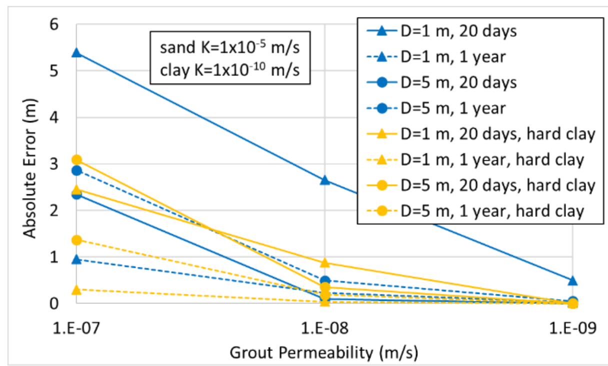

Figure 8. Sensitivity of the absolute piezometer error to the clay stiffness

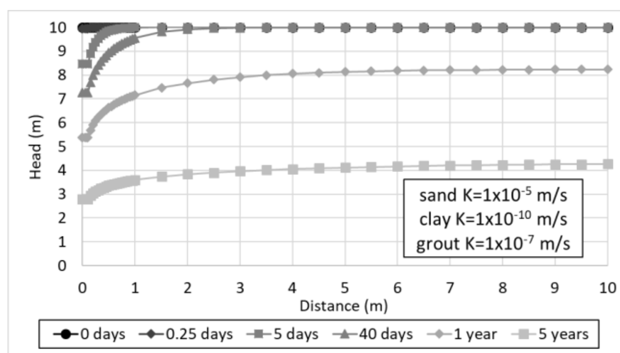

Figure 9. Hydraulic head vs distance from the borehole, 5 m below top of clay layer, grout permeability 1x10^{-7} m/s

5 OBSERVATIONS OF FIELD PERFORMANCE

5.1 Muskeg River Mine In-Pit Dykes

The in-pit dykes at the Albian Sands Muskeg River Mine (MRM) in the Alberta oil sands region are constructed with low permeability compacted lean oil sand mine waste fill. The foundation soils typically consist of a permeable sand at the bottom of the mine pit, overlying limestone and calcareous shale, with a weathered zone at the contact.

To monitor the pore pressure responses during construction and impoundment, VWPs are installed in the foundation units and dyke fills.

Several FGM piezometer installations in the in-pit dyke fill and foundation were interpreted to be influenced by hydraulic short-circuits. Figure 10 shows the design cross section of In-Pit Dyke 2 and Figure 11 shows the response of typical FGM piezometers in a single borehole. The grout mix used for the piezometer installation was 2/1/0.48 water/cement/bentonite (w/c/b). The geological setting includes a continuous sand layer under the dyke.

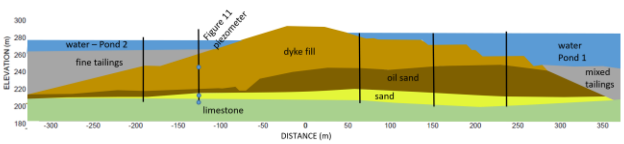

Figure 10: MRM In-Pit Dyke 2 Section

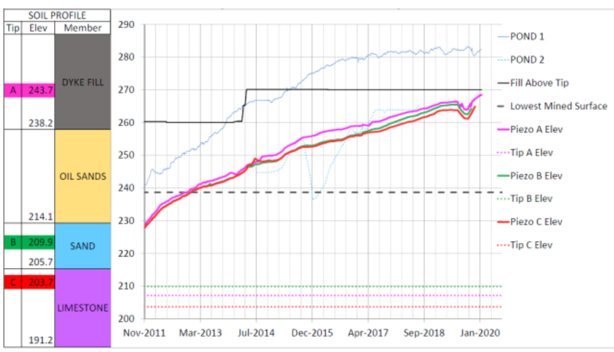

Figure 11: MRM In-Pit Dyke 2 – FGM piezometer data

The three piezometers are located adjacent materials of significantly different permeability: high permeability sand, and low permeability lean oil sand fill (upper tip) and limestone (lower tip). However, all three tips show the same response to seepage from the adjacent pond, which flows to the borehole location through the sand layer. It is therefore likely that the grouted borehole is providing a hydraulic connection to the sand layer.

Two practical issues were considered to have contributed to high effective grout permeability and piezometric errors:

- Differential settlement leading to cracking in the grout column, due to a difference in stiffness between the grout and surrounding soil, can create hydraulic short circuit in the borehole.
- Difficulty in consistently mixing and delivering a grout to the target elevation that had a permeability lower than the surrounding formation.

5.2 Jackpine Mine External Tailings Facility

A series of 7 twinned piezometers were installed in the Cretaceous Clearwater formation clay-shale at the Albian Sands Jackpine Mine External Tailings facility. The Clearwater formation is a heavily overconsolidated, high plastic clay-shale with very low permeability, in the range of 10^{-11} to 10^{-14} m/s. For each twinned installation, one piezometer was installed using the FGM in a borehole with an inclinometer casing, and a second using the sandpack method in a parallel hole approximately 3.5 m to 5 m away. The two piezometer tips were typically within 0.1 m elevation. The boreholes were drilled through tailings sand (approximate permeability 2×10^{-5} m/s) and then into the foundation. The Clearwater Formation is known to exhibit a very high pore water pressure response to a change in vertical total stress ($\bar{B}$ typically 0.8 +/- 0.2). Prior to installation of the piezometers, a total fill thickness of 14 m to 18 m was placed at the piezometer locations over a period of 2 years, and so very high excess pore water pressures were anticipated within the Clearwater formation. The design grout mix for the FGM piezometers was the standard 2.5/1/0.3 w/c/b mix recommended by Mikkelsen (2002) for medium-hard soils, though the bentonite content was varied for some installations.

In 5 out of 7 twinned boreholes, the FGM installations read approximately hydrostatic pressures based on the water table in the overlying tailings sand, and did not record the anticipated very high pressures in the Clearwater formation. In all cases the sandpack installations recorded high excess pore pressures which were considered credible and consistent with the expected response based on extensive industry experience with this geologic formation. An example of piezometer data showing a significant different response between two parallel installations is shown on Figure 12, with the FGM piezometer reading hydrostatic pressure below the overlying sand, and the sandpack piezometer reading the pressure resulting from the fill loading. The FGM installation appears to have a hydraulic short circuit, so that it does not accurately report the pore pressure. In this instance, relying on the FGM data would yield a significantly unconservative factor of safety for an assessment of the tailings dam stability.

Other piezometers were installed at the site beside the SI casing using the FGM within the permeable tailings sand where the grout was less permeable that the adjacent soil; those instruments appear to respond well to the pore pressure changes within the expected range and show good agreement with other tips installed using the sandpack and bentonite chip seal method.

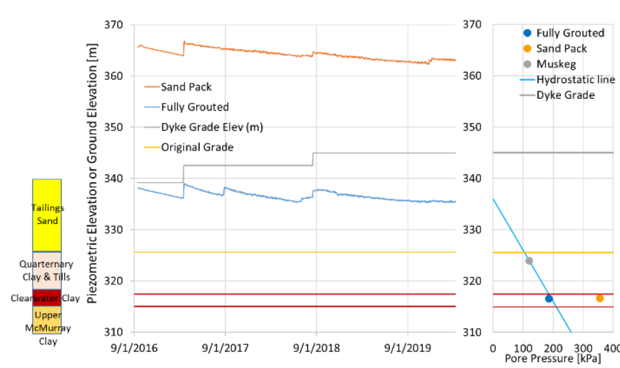

Figure 12. Example of twinned FGM and sandpack piezometer installation and head-time data.

6 CONCLUSIONS

6.1 Application of study results

Much of the earlier literature that promoted the fully grouted method (Vaughan, 1969, Contreras et al. 2008 and 2012, Mikkelsen, 2002, Mikkelsen and Green, 2003) did so on the basis of conclusions derived for assessment of very simplistic conditions with homogenous geology and the borehole not penetrating multiple layers, and steady state flow conditions. Vaughan (1969) concluded “In *certain configurations*, the permeability of the grout plug can be several orders of magnitude greater than the soil without significant error resulting.” (emphasis added) Unfortunately, some authors and practitioners have taken this sentence to be true for all conditions, and have advocated moving completely away from the sandpack and bentonite seal method, and endorsed the FGM without consideration of all the situations where the method could yield inaccurate results. Previous modelling results under homogeneous, steady state conditions should not be used to infer the universal validity of the FGM.

A more thorough examination of the conditions under which the FGM is reliable is presented by Marefat et.al. (2018). This present study supports the conclusions of Marefat et al. (2018) and has demonstrated that errors due to transient pore pressures induced by external loading are likely to be in the unconservative direction, so it is essential to understand the conditions for which the FGM is reliable.

There are several broader lessons for the geotechnical profession arising from this examination of the effectiveness of the FGM:

- Critically examine published findings before fully adopting them. Understand the conditions under which any analytical or field procedure was derived, and the limitations of the applicability of that procedure. Procedures that are applied to situations that are outside their range of demonstrated validity may lead to erroneous results.
- Understand that with various in-situ measurements, and particularly for piezometers, what is actually measured may not be what is intended to be measured. The more complex the stratigraphy and flow system, the more likely that the measurements are not the actual pore pressures in the adjacent soil.

6.2 Grout permeability ratios from numerical models

As other researchers have found, the errors for readings under steady state conditions may be acceptable with a grout/formation permeability ratio of 100. Under these conditions, with a constant gradient across the clay layer, the error is greatest distant from the sand-clay interface.

For transient flow, for the conditions modelled in this study the errors are small for a 10x permeability ratio between the grout and formation, at all practical distances from the interface and all times beyond the first few days following loading.

At a 100x permeability ratio, the errors can be large near a stratigraphic interface, for times in the range of weeks to months. At times of the scale of a year or more, the error becomes small. At a 1000x ratio, the errors can be large for greater distances from the interface, and for extended periods of time.

For conditions where the pore pressure increases uniformly in a clay layer due to application of an external load so that there is no initial gradient across the clay layer, the error is greatest near the sand-clay interface.

6.3 Observations from field installations

An examination of the data from twinned FGM and sandpack piezometers installed in clays where the grouted section passes through a sand demonstrates that the grout can provide a hydraulic connection to the higher permeability materials, and accuracy of readings become highly dependent on the grout mix quality and its permeability. The measured pore pressures may be strongly influenced by the pressures in higher permeability layers adjacent to the layer of interest.

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