Geomechanics and Engineering, *Vol. 33, No. 5 (2023) 519-528*
https://doi.org/10.12989/gae.2023.33.5.519

Effects of polymer support fluid on shaft resistance of offshore bored piles

Chungsik Yoo* and Chun-Won Shin[a]

School of Civil, Architectural Engineering and Landscape Architecture, Sungkyunkwan University,
2066 Seboo-ro, Jangan-gu, Suwon, Gyeonggi-do 16419, Republic of Korea

(*Received October 5, 2021, Revised May 2, 2023, Accepted May 3, 2023*)

Abstract. In this paper, we present the results of an experimental study on the effect of polymer support fluid on shaft resistance of offshore bored piles. A series of pullout tests were performed on bored piles installed under various boundary conditions considering different types of grounds and support fluids, and a range of support fluid exposure times. Contrary to previous studies concerning onshore bored piles, a time dependent effect of polymer fluid on shaft resistance was observed in all ground types. The adverse effect of polymer support fluid on the shaft resistance, however, was considerably less than bentonite support fluid for a given exposure time. No significant reduction in shaft resistance was evident when limiting the exposure time of the polymer support fluid to the side wall of the borehole within 2-3 hours. The degree to which the polymer fluid affects shaft resistance seemed to vary with the ground type. A proper consideration should be given to the time dependent effect of polymer fluid on shaft resistance of bored piles installed in offshore construction environment to limit its adverse effect on the pile performance. The practical implications of the findings are discussed.

Keywords: bentonite; bored pile; filter cake; offshore pile construction; polymer; shaft resistance; support fluid

1. Introduction

When constructing bored piles (drilled shafts), support fluids are used to provide hydrostatic pressure to prevent borehole collapse. Bentonite fluids, known as mineral slurries, have been extensively used in bored pile construction. Synthetic polymer-based support fluids made from acrylamide and acrylic acid (specifically anionic polyacrylamide or PAM) have also been used in bored pile construction since the 1980s (Brown *et al.* 2010). Selecting a proper type of support fluid for a specific site is an important part of successful bored pile construction.

A concern that often arises pertains to the possibility that shaft resistances could be adversely affected by the use of a support fluid in bored pile construction. For example, it is postulated that bentonite filter cake formed on the sidewalls of a borehole could create an interface that is weaker in shear than would be the case in the absence of support fluid, thereby reducing the shaft resistance of bored piles. Several earlier studies (Nash 1974, Farmer and Goldberger 1969, Wates and Knight 1975, Cernak 1976, Fleming and Sliwinski 1977, Cooke 1979, Majano and O'Neill 1993, O'Neill and Hassan 1994) have reported the effect of bentonite fluid on shaft resistance ranging from minimal to significant reduction. These studies in fact highlighted the importance of minimizing the exposure time of bentonite fluid to the sidewalls of a borehole in avoiding the potentially detrimental effect of bentonite support fluid on the shaft resistance of bored piles.

Polymer-based support fluids are becoming popular for use in various types of soils/rocks in bored pile construction. Long, chain-like hydrocarbon molecules in synthetic polymers allow the formation of a polymeric membrane on the borehole sidewall, which controls fluid loss and exerts positive pressure against the borehole sidewall. When the polymer fluid is used, no filter cake is formed unless the polymer fluid contained significant amounts of trapped colloidal fines (Brown *et al.* 2010, Iqbal *et al.* 2019, Lam and Jefferis 2015). As the polymer fluid itself has a slimy texture, however, it could lubricate the soil-concrete interface.

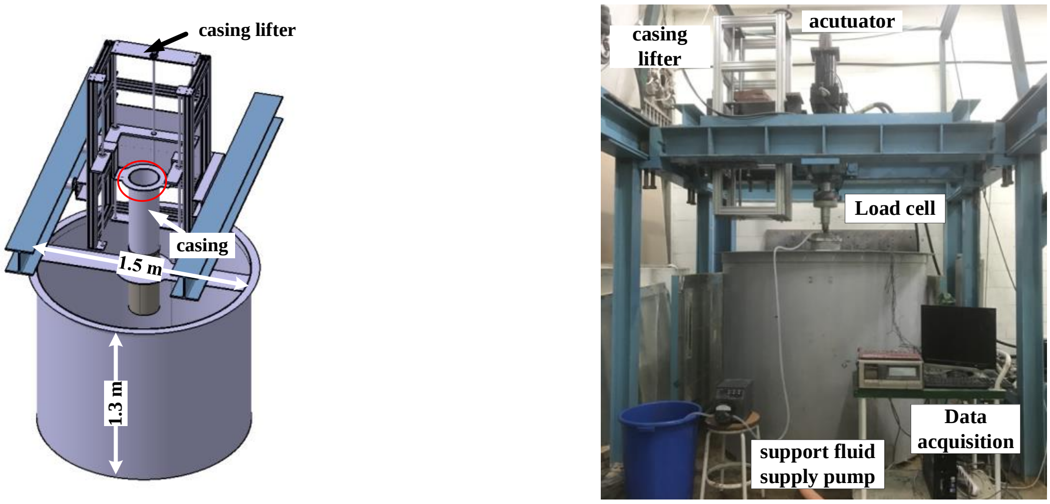
Only a few studies have been conducted on the effect of polymer-based support fluid on the shaft resistance of bored piles. One of the earlier studies may perhaps be the one by O'Neill and Hassan (1994). They conducted load tests on five drilled shafts in sandy silt to silty sand constructed under a polymer fluid, and they reported a slight reduction in the side resistance relative to the value expected without a polymer fluid. Majano *et al.* (1994) on the other hand showed a slight increase in side friction of model drilled shafts with time of exposure of polymer support fluid to the soil prior to concrete placement using two types of polymer support fluids. A comparative test in saturated sand/gravel/coble alluvium by Meyers (1996) showed that the drilled shaft constructed with the polymer fluid developed higher side resistance than the shaft constructed with bentonite fluid. Ata and O'Neill (1997) also reported no or minimal effect of polymer-based support fluid on drill shaft side resistance. Several comparative studies between bentonite and polymer support fluids have also reported either no discernible differences in shaft resistance of bored piles installed in low-permeability material (Camp *et al.* 2002, Frizzi *et al.* 2004) or significantly lower shaft

---

*Corresponding author, Professor
E-mail: csyoo@skku.edu
[a]Former MSc Student

http://www.techno-press.org/?journal=gae&subpage=7

ISSN: 2005-307X (Print), 2092-6219 (Online)



(a) Test setup details

(b) photo of completed setup

Fig. 1 Experimental test setup

resistance when using bentonite than polymer for drilled shafts installed in a permeable material (Brown 2002). Lam *et al.* (2015) and Lam and Jefferis (2016) used a field trial to show that piles constructed using polymer fluids had stiffer load-settlement response than the one constructed using bentonite slurry. Most recently, Yoo and Han (2019) reported that bentonite fluid significantly decreased the concrete-soil/rock interface shear strength, while a negligibly small effect was observed for polymer fluid based on the results of interface shear strength tests using a custom-designed shear box considering seawater drilling environment.

Although the previous studies provided insights into the governing mechanisms involved in the effect of polymer support fluids on the shaft resistance of bored piles, they do not provide a consistent baseline that can be extended to practice. Additionally, no offshore bored pile construction cases were considered, where the groundwater chemistry is much different from that of the inland construction environment. The discrepancies between the reported results and the scarcity of studies concerning offshore bored pile construction environment indicate the urgency of research to quantify the extent to which polymer fluids affect shaft resistance of bored piles under offshore construction environment.

In this paper, we present the results of an experimental investigation into the effect of polymer support fluid on shaft resistance of bored piles installed under an offshore construction environment. A series of pullout tests were performed on bore piles installed under various boundary conditions, considering different types of grounds and support fluids, and a range of support fluid exposure times, using a model test setup that can simulate the bored pile construction process. The results are presented in this paper so that the effect of polymer support fluid on bored piles installed under various offshore construction conditions can be identified. A comparison between polymer and bentonite fluids was also made for a selected case.

2. Reduced-scale model test

2.1 Test setup and model bored pile

The pullout tests were carried out in a model test setup capable of simulating offshore bored pile construction including (a) creation of a borehole, (b) support fluid injection and filtration into model ground, (c) concrete casting for a model pile, and (d) loading. The test setup shown in Fig. 1 consists of a steel tank and a loading system together with other auxiliary devices simulating bored pile construction. The steel tank, made of a 5 mm thick steel plate, had a diameter of 1500 mm and was 1300 mm in height. The auxiliary devices shown in Fig. 1(a) include a casing, an automatic casing removal system, a support fluid supply controller, and a pullout device.

Model bored piles (0.2 m in diameter and 0.6~0.65 m in length) were casted using salt resistant cement, which is used in construction of offshore structures. A cement-water mix ratio of 2.4 kg per 1 litre was adopted to make cement paste with a specific weight of 1.9. To expedite the concrete curing process, a fast-curing accelerator and superplasticizer, 5% and 0.01% by weight, respectively, were added to the cement-water mix.

Pullout load was applied to model piles using a specially devised guide frame installed during the pile casting stage. A 10-ton capacity, multi-purpose hydraulic loading system capable of applying monotonic and cyclic loading in a load-controlled as well as displacement-controlled manner was used to apply the load. Pullout load and vertical displacement at the head of a model pile were measured using a 10-ton load cell and a 200 mm-gauge length LVDT, respectively [Fig. 1(b)].

All model tests were conducted under a subaqueous environment using seawater, which was artificially made by mixing 38.2 g of sea salt named “Red Sea Salt” to 1 litre of fresh water to have a typical salinity of 35.5%. Details of the key chemical components of the artificially made seawater can be found elsewhere (Yoo 2017).

Table 1 Geotechnical properties of ground layers

Material	Young's modulus, E (MPa)	Poisson's ratio, ν	Cohesion, c' (kPa)	Internal friction angle, ϕ' (°)	Unit weight, γ (kN/m^3)
Fill	20	0.32	21	29	20
Weathered rock	290	0.30	70	32	22
Soft rock	910	0.27	440	37	24

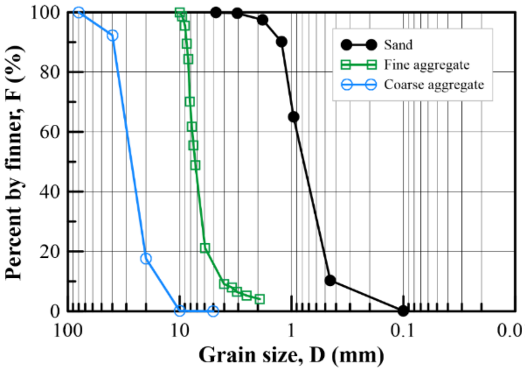
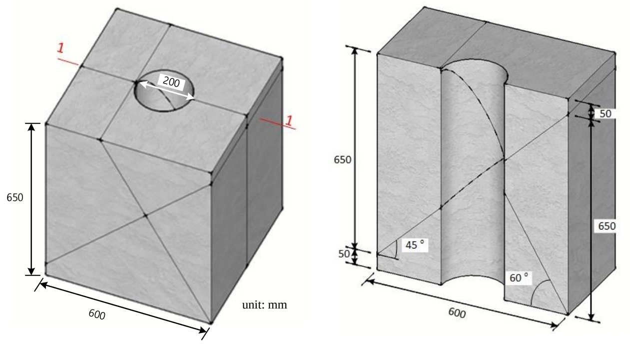


Fig. 2 Grain size distribution curves for sand and fine/coarse aggregates



(a) jointed rock overlooking view

(b) cross section

Fig. 3 Schematics of jointed rock blocks

2.2 Model ground

Three different soil/rock types were considered in this study, namely sand, sandy gravel, and jointed rock, to represent a broad range of ground conditions. Geotechnical properties of the model ground are summarized in Table 1.

2.2.1 Sand

Junmunjin standard sand, classified as SP per ASTM 2487-11, was used to form the model sand bed. Sand has an effective size (D_{10}) defined as the diameter in the particle-size distribution curve corresponding to 10% finer, uniformity coefficient ($C_u = D_{60}/D_{10}$), and coefficient of curvature ($C_c = \frac{D_{30}^2}{D_{10}D_{60}}$) of 0.36 mm, 5.3 and 1.1, respectively, as shown in the grain size distribution curve (Fig. 2). The model sand bed was created in the test tank at a target relative density of 70%, representing a dense condition. The estimated peak effective internal friction angle (ϕ') at the target relative density was $\phi' = 30°$ with zero cohesion intercept based on the direct shear tests conducted under the normal stress range $50 - 150$ kPa.

The hydraulic conductivity of as tested condition was approximately $k_{sand} = 2 \times 10^{-4}\ cm/s$. Note that the effective friction angle measured from the direct shear test is a bit lower than the typical value for a sand with 70% relative density. Although the exact reason is not known, repeated use of the sand for tests may have caused this discrepancy.

2.2.2 Sandy gravel

Sandy gravel model ground was created using fine and coarse crushed aggregates together with sand to have a target unit weight of 20 20 kN/m^3. The required weights of aggregates and sand to fill the test tank for the target unit weight was first determined by considering the volume of the test tank. The test tank was then filled with aggregates and sand of the pre-determined weights in three layers to have a densely packed sandy gravel model ground. Fig. 2 shows particle size distribution curves of the coarse and fine aggregates. A series of large-scale direct shear tests on specimens prepared at the target unit weight yielded a peak effective internal friction angle of $\phi' = 37°$ with zero cohesion intercept. The hydraulic conductivity of the model sandy gravel ground was approximately $k_{sandy\ gravel} = 5 \times 10^{-2}\ cm/s$.

2.2.3 Jointed rock

Precast concrete blocks including two discontinuities, crossing the borehole with dip angles of 45 and 60 degrees, were used to form jointed rock model ground (Fig. 3). The concrete blocks were prepared in a mold having a plan dimension of 0.6 m by 0.6 m with a height of 0.65 m by casting the same cement mortar used for the model bored pile. A 0.2 m diameter steel pipe was placed to form the borehole when casting the blocks. The mold was devised to be split in half as shown in Fig. 3 to facilitate the formation of discontinuities, placement of cement mortar, and demolding of cured concrete blocks. The discontinuities were created by placing two 3 mm thick plywood sheets at the designated dip angles immediately after pouring concrete mix. Fully cured precast concrete blocks were then assembled in the test tank to form the jointed rock model ground. Note that the jointed rock cases were intended to study the effect of polymer fluid on the shaft and rock interface when used as drilling fluid (not as a support fluid to prevent borehole collapse).

2.3 Support fluids

Two types of polymers, P1 and P2, from different

Table 2 Properties of support fluids

Property	Test method	Unit	Drilling fluid			Compliance values for bentonite fluid according to Institution of Civil Engineers (2007)
			Polymer		Bentonite	
			P1	P2		
Density	Mud balance	g/cm^3	1.014	1.022	1.052	< 1.1
Fluid loss at 30 min	Fluid press	ml	44	71	14.7	< 30
Filter cake thickness at 30 min	Micrometer	mm	-		6.35	< 3
Marshal funnel viscosity	Marsh funnel	s	64	93	42	30 - 50

Table 3 Summary of pullout test series

Series	Base material	Support fluid	Exposure time (h_{ex})
A	Sand	Seawater* Bentonite Polymer (P1)	12
B	Sand, Sandy gravel, Jointed rock	Polymer (P1)	2, 12, 24
C	Jointed rock	Polymer (P1 & P2)	24

manufacturers, were used in this study which are synthetic anionic polyacrylamide polymers in granular form. Note that P1 polymer was used in the main test series, while P2 polymer was considered to make a comparison with P1 polymer for a selected case. Different dosages were used for P1 and P2 polymers as suggested by manufacturers. For P1 polymer fluid, the polymer was mixed at a dosage of $1\ kg/m^3$ with a performance enhancing additive of $0.02\ kg/m^3$ to provide a membrane effect by transforming the polymer into a gel. For P2 polymer fluid, $0.7\ kg/m^3$ of polymer was mixed with water together with 1.2 g of potassium hydroxide to buffer the fluid to pH=11. 8%. Sodium-activated bentonite fluid (8%) was also used to make a direct comparison with P1 polymer fluid. Key properties of the polymer and bentonite support fluids are shown in Table 2 which were determined using the methods prescribed by the API (American Petroleum Institute) standard methods (API 2003).

2.4 Test conditions

As summarized in Table 3, three test series were devised including 13 test cases. *Series A* concerned the effect of polymer relative to the bentonite fluid while *Series B* considered the time dependent effect of polymer fluid considering a range of exposure times of support fluids in the borehole before casting concrete, known as filtration times (h_{ex}), i.e., $h_{ex} = 2, 12, 24\ h$ and the relative effect of polymer fluid on different ground types, Finally, *Series C* was devised to focus on the effect of polymer fluid type. Note that in all test cases artificially made seawater was used to simulate the offshore drilled shaft construction environment. All test cases were repeated multiple times until a desired repeatability was achieved, i.e., within ±10% in terms of peak pullout force $\left(P_{po}\right)_{peak}$.

2.5 Test procedure

The reduced-scale model test procedure involved five key stages: (a) model ground preparation including saturation, (b) formation of a borehole with support fluid injection, (c) concrete casting for bored pile, and (d) pullout loading. Details are given below with schematic diagrams of the test procedure (Fig. 4).

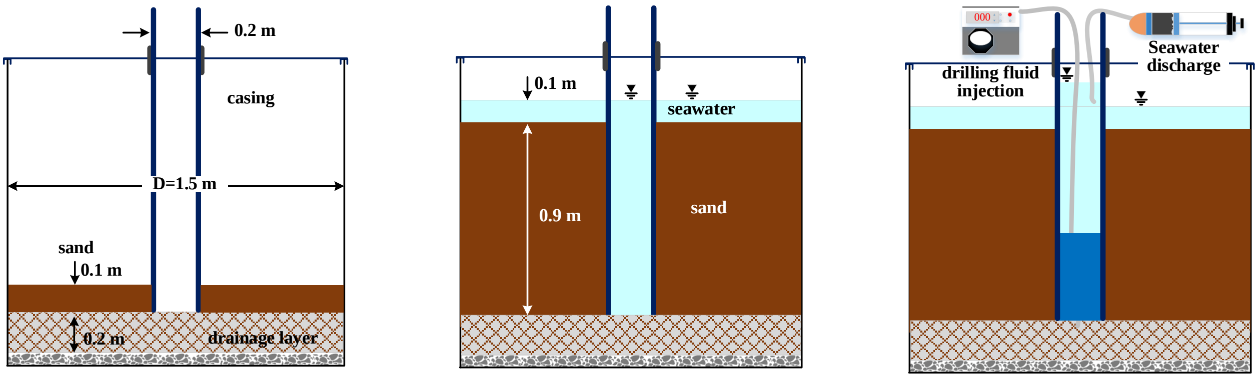
Model ground preparation

For sand ground, a 0.2 m thick gravel drainage layer was first placed on top of a geotextile filter layer to facilitate the drainage of seawater during and after the test [Fig. 4(a)]. After placing an additional 0.1m thick sand layer at a relative density of 70%, a 0.2 m diameter, 1.0 m long casing was placed down on the top of the gravel layer. Sand was then pulvinated to create an additional 0.8 m thick sand bed using a raining device at a discharge height of 0.1 m to have the target relative density of 70% [Fig. 4(b)]. The discharge rate and height during sand pluviation were carefully controlled to obtain consistent soil densities and placement conditions of the model sand bed in a series of tests. Upon completion, the model sand bed was flooded with seawater for 6 hours with the bottom drainage valve open for saturation [Fig. 4(b)]. The bottom valve was then closed, and the tank was filled with seawater until the seawater level reached 0.1 m above the top surface of the sand layer [Fig. 4(b)]. A similar approach was adopted for the sandy gravel model ground.

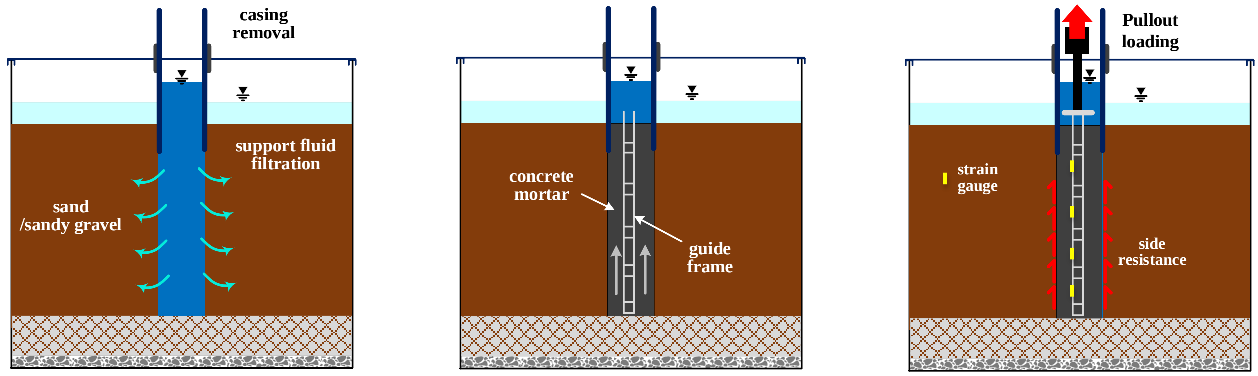
For jointed rock, the precast concrete blocks were first assembled in the test tank immediately after the placement of the bottom drainage layer. The remaining portion of the test tank was then filled with sand so that the entire jointed rock blocks were buried at a burial depth of 0.2 m. Note that the space between the discontinuities was filled with kaolin mixture to mimic gouge formation along discontinuities. After formation of the jointed rock model ground, the same saturation process was undertaken.

Formation of borehole with support fluid injection

Upon completion of the model ground formation, the seawater inside the casing was replaced by support fluid using an automatic injection controller [Fig. 4(c)]. Note that the support fluid was injected from the bottom while



(a) drainage layer placement (b) formation of sand bed (c) drilling fluid injection



(d) support fluid filtration (e) pile casting (f) pullout loading

Fig. 4 Schematics of model preparation procedure

simultaneously removing the seawater from the borehole using a plastic tube as shown in the photo [Fig. 4(c)]. After feeding the support fluid, the casing was then pulled out using the automatic pullout device [Fig. 4(d)]. To ensure the borehole stability, the support fluid level was kept 200 mm above the piezometric level of the model ground. Support fluid exposure to the borehole was then allowed for a designated time (filtration process).

Bored pile installation

After completion of the filtration process, a 150 mm diameter concrete delivery tube was inserted down to the bottom of the borehole to deliver a super plasticized, self-consolidating concrete mortar to cast a pile [Fig. 4(e)]. The support fluid in the borehole was automatically flushed with the concrete mortar due to the difference in the density of the two materials. As shown in Fig. 4(e), a strain gauges attached guide frame was then placed at the center location of the borehole immediately after the concrete placement. The concrete mortar was left 36 hours for curing.

Pullout load application

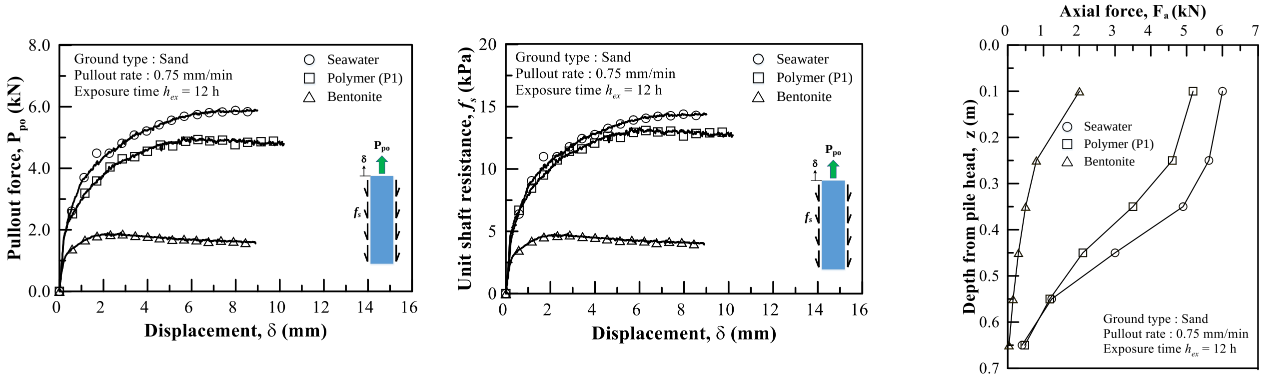
Upon completion of the 36-hour curing process of the model bored pile, pullout load was applied to the model pile by pulling the guide frame using the displacement controlled hydraulic loading system [Fig. 4(f)]. The pullout load was applied at a rate of 0.75 mm/min considering the suggested range of loading rate of 0.5-1.0 mm/min per ASTM D3689. During the pullout loading, a 10-ton load cell and internal displacement gauge were used to collect the applied load and displacement data.

3. Results and discussion

The results of pullout tests are presented in the form of pullout force-vertical displacement ($P_{po} - \delta$), unit shaft resistance-vertical displacement ($f_s - \delta$), and axial force-depth ($F_a - z$) curves. For cases where $P_{po} - \delta$ curves showed the hardening behavior a pullout force at the pullout displacement of $\delta = 3\%$D (D=pile diameter) was selected as peak value ($\left(P_{po}\right)_{peak}$ to ensure the consistency in determining $\left(P_{po}\right)_{peak}$, and thus $(f_s)_{peak}$. Note that the unit shaft resistance (f_s) was calculated by dividing the measured pullout force (P_{po}) with the contact area between the pile shaft and the surrounding ground, considering the method adopted by Hsiao *et al.* (2020) for jointed rock cases. Axial forces in the model pile were inferred from the measured axial strains along the guide frame assuming full bonding between the guide frame and the model pile.

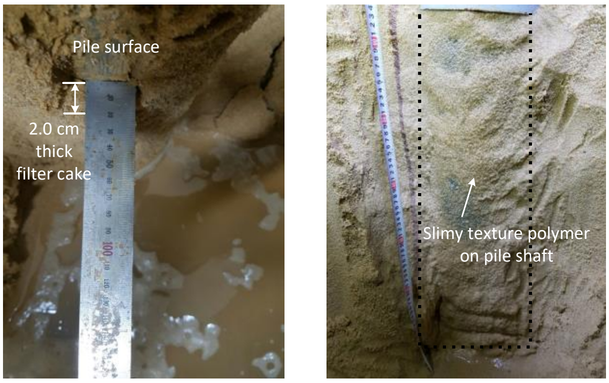
3.1 Effect of polymer support fluid

A The effect of polymer support fluid relative to that of the bentonite fluid on the shaft resistance of a bored pile installed in sand was examined for an exposure time of $h_{ex} = 12\,h$ in Fig. 5. A seawater support fluid case with



(a) $P_{po} - \delta$ (b) $f_s - \delta$ (c) $F_a - z$

Fig. 5 Effect of type of support fluid on pullout force and side resistance (sand)



(a) bentonite (b) polymer (P1)

Fig. 6 Filter cake (bentonite) and slimy texture polymer on pile shaft ($h_{ex} = 12\ h$)

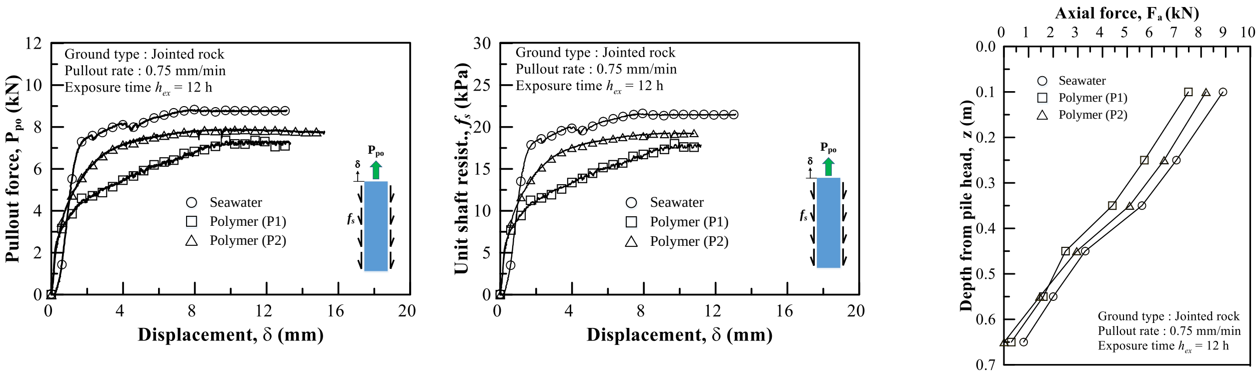
$h_{ex} = 0$ was also shown as a reference case. Any differences between the polymer and the bentonite fluid cases are due to the type of fluid, as all other factors were kept unchanged. Note that the exposure time of $h_{ex} = 12\ h$ represents rather a severe case of exposure of support fluid to the borehole sidewall before pile casting.

In the pullout force – displacement ($P_{po} - \delta$) and unit shaft resistance – displacement ($f_s - \delta$) curves shown in Figs. 5(a) and 5(b), respectively, it can be noticed that the seawater and the bentonite fluids, respectively, define the upper and lower bounds, while the polymer fluid falls between the two. Both the polymer and bentonite fluids decreased the shaft resistance when compared to the seawater case but with a considerably smaller decrease in the polymer fluid than the bentonite fluid for the given exposure time of $h_{ft} = 12\ h$. More specifically, in terms of peak unit shaft resistance $(f_s)_{peak}$, the bentonite fluid decreased $(f_s)_{peak}$ by 65% from the reference case, whereas only a 15% reduction occurred when using the polymer fluid. Such trend can also be observed in $F_a - z$ curve shown in Fig. 5(c) where the axial forces are plotted against depth. Such a large reduction when using the bentonite fluid was due to the 2.0 cm thick filter cake formation on the shaft surface, as shown in Fig. 6(a). No filter cake formation was observed in the polymer case although slimy texture polymer remained on the pile surface [Fig. 6(b)], which likely caused the decrease in the shaft resistance by providing a lubricating effect to the interface between the shaft and the ground. Yoo and Han (2019) also reported the slimy texture polymer remaining on concrete surface in their study concerning the effect of drilling fluid on concrete-soil/rock interface shear strength in a seawater drilling environment. The results above are in line with the study by Brown (2002) which reported a much smaller effect of polymer drilling fluid on shaft resistance when compared with bentonite drilling fluid for a given exposure time.

Majano *et al.* (1994) investigated the effect of type of polymer fluid on the side resistance of drilled shafts. They reported a greater reduction in unit load transfer values when using emulsified partially hydrolyzed polyacrylamide (PHPA) polymers than dry vinyl polymers, suggesting that the type of polymer fluid and dosage could affect the drilled shaft performance. To confirm their finding, an additional test was performed using P2 polymer fluid for a bored pile installed in jointed rock with an exposure time of 12 hours. As shown in Fig. 7, it is apparent that P2 polymer fluid outperformed P1 polymer fluid, although ultimate values seem to have remained the same. More specifically, when expressed in terms of the unit shaft resistance ratio, $\left(\frac{f_s}{f_s^{sw}}\right)_{peak}$ _peakvalues for P1 and P2 polymers were 0.75 and 0.9, respectively, indicating a 25% and 10% reduction from the seawater case. Although further studies are required to draw a general conclusion, such results highlight the importance of considering polymer type and its dosage in view of maximizing the load transfer characteristics of bored piles.

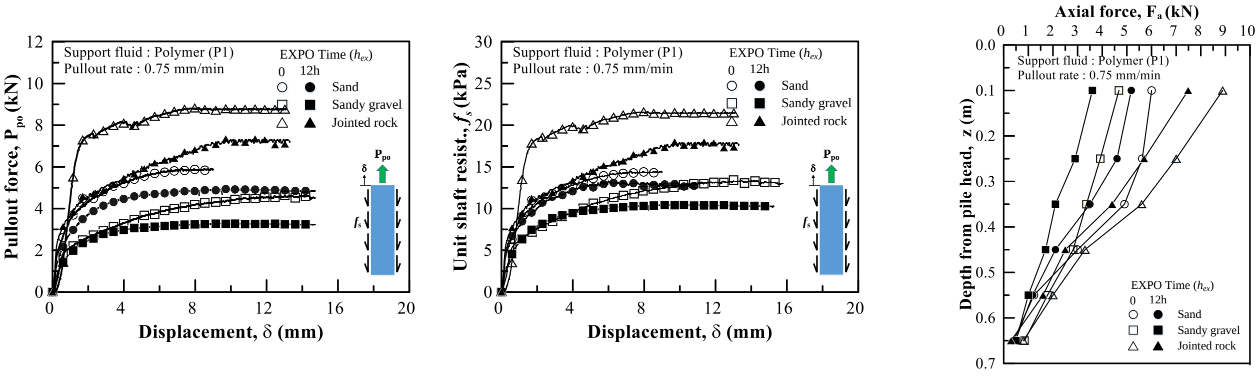
3.2 Effect of ground type

The relative effect of polymer fluid on different ground types (sand, sandy gravel, and jointed rock) was investigated for a given exposure time of 12 h, and the results are shown in Fig. 8. As can be seen in these figures where $P_{po} - \delta$, $f_s - \delta$, and $F_a - z$ curves are shown, the polymer fluid reduced the shaft resistance of bored piles installed in all ground types when allowed the borehole to be exposed to support fluid for 12 h. The degree of



(a) $P_{po}-\delta$ (b) $f_s-\delta$ (c) F_a-z

Fig. 7 Effect of type of polymer on pullout force and shaft resistance (jointed rock, $h_{ex}=12\ h$)



(a) $P_{po}-\delta$ (b) $f_s-\delta$ (c) F_a-z

Fig. 8 Variation of effect of polymer fluid on shaft resistance with ground type (P1 Polymer, $h_{ex}=12\ h$)

reduction, however, seemed to vary with the ground type, showing a largest reduction when installed in sandy gravel, followed by jointed rock and sand. More specifically, in terms of the normalized values, i.e., $\left(P_{po}/P_{po}^{sw}\right)_{max}$ and $(f_s/f_s^{sw})_{peak}$, in Fig. 9, $\left(P_{po}/P_{po}^{sw}\right)_{peak}$ are 0.86, 0.71, 0.84, respectively, for sand, sandy gravel, and jointed rock, representing 14%, 29%, and 16% of reduction.

A similar trend can be observed in the unit shaft friction ratio $(f_s/f_s^{sw})_{peak}$ showing a 10%, 24% and 18% reduction for sand, sandy gravel, and jointed rock, respectively, from the reference case (seawater). It is worth noting that the pullout resistance of the sandy gravel is lower than that of the sand despite the greater friction angle of the original ground, i.e., $\phi_{sand}=30°$ vs. $\phi_{sandy\ gravel}=37°$. This is because the bore hole stability of the sandy gravel case was not as firmly maintained as for the sand case even, thus giving a lower pullout capacity for the sandy gravel than the sand.

The results presented above suggest that the degree to which the polymer fluid affects the shaft resistance varies with the ground type, which seems to contradict previous studies (Majano *et al.* 1994, Ata and O'Neill 1997, Lam *et al.* 2015) concerning onshore construction, in which no appreciable decreases were reported for bored piles installed in various types of ground. Moreover, the reduction of 18% observed in the jointed rock case is somewhat unexpected considering its impermeable nature.

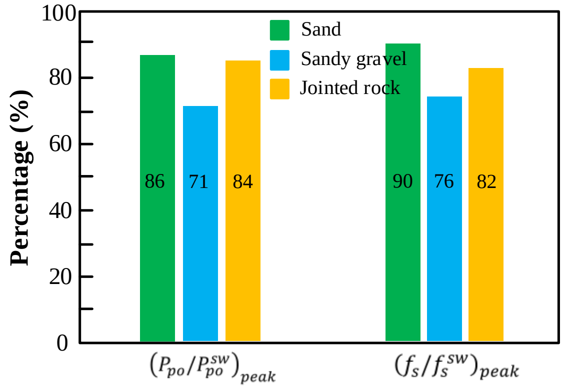
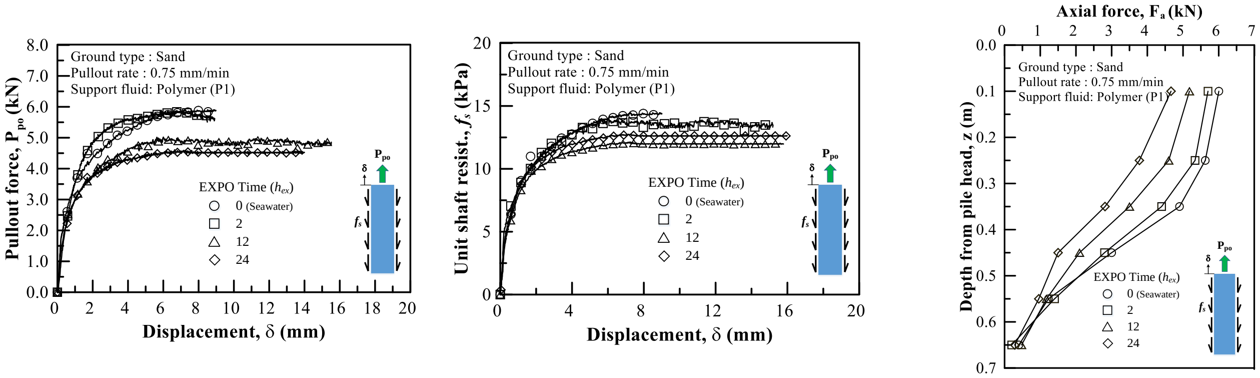


Fig. 9 Variation of effect of polymer fluid on $\left(P_{po}/P_{po}^{sw}\right)_{peak}$ and $(f_s/f_s^{sw})_{peak}$

Differences in the groundwater chemistry between the current study focusing on offshore pile installation and the previous studies concerning onshore might have been the major cause. A further study is necessary to draw definitive conclusions on the effect of polymer fluid on the shaft resistance of bored piles in offshore environment.

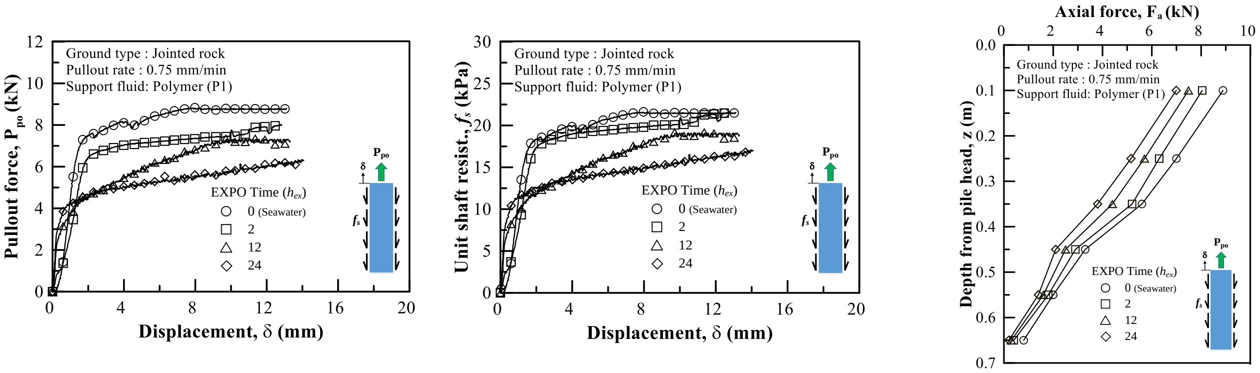
3.3 Effect of exposure time

There have been conflicting reports regarding the effect of exposure (filtration) time of polymer fluid on the side



(a) $P_{po} - \delta$ (b) $f_s - \delta$ (c) $F_a - z$

Fig. 10 Effect of exposure time (h_{ex}) on pullout behavior (sand)



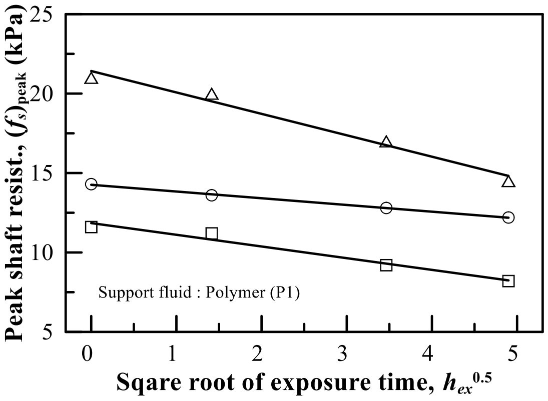
(a) $P_{po} - \delta$ (b) $f_s - \delta$ (c) $F_a - z$

Fig. 11 Effect of exposure time (h_{ex}) on pullout behavior (jointed rock)

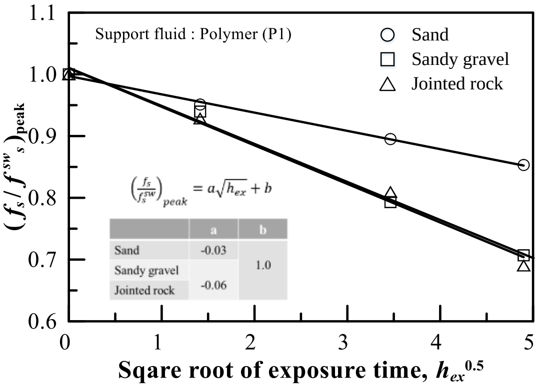
resistance of drilled shafts (Majano *et al*. 1994, Brown 2010, Lam *et al*. 2015). Therefore, the effect of exposure time of polymer fluid (P1) under offshore construction environment was further investigated in this study considering a range of exposure times, i.e., $h_{ex} = (2-24)\,h$ for bore piles installed in the various ground types.

Figs. 10 and 11 show the pullout force-displacement ($P_{po} - \delta$), unit shaft resistance-displacement ($f_s - \delta$), and axial force-depth ($F_a - z$) curves for bore piles installed in sand and jointed rock under various exposure times. Note that those for sandy gravel are not presented here due to space limitation but are available elsewhere (Yoo 2017). In each curve, the results for the reference case, i.e., seawater with $h_{ex} = 0\,h$ are also presented. In Fig. 10 where the results for sand are shown, no significant effect of polymer fluid on the shaft resistance is observed in $P_{po} - \delta$, $f_s - \delta$, and $F_a - z$ curves for the first 2 hours of exposure time. A further increase in the exposure time beyond 2 hours however considerably reduced the unit shaft resistance, e.g., a decrease in $(f_s)_{peak}$ by as much as 12%, suggesting a clear time dependent effect of polymer fluid on the shaft resistance in case of offshore bored piles. As shown in $F_a - z$ curve in Fig. 10(c), the decrease was more or less uniform along depth up to 0.5L (L=shaft length) below which a sharp decrease towards the pile tip was observed. The results for jointed rock in Fig. 11 also show decreases in the shaft resistance with an increase in exposure time. In fact, the peak unit shaft resistance $(f_s)_{peak}$ decreased by approximately 30% when increasing the exposure time from 0 to 24 h.

The time dependent effect of polymer fluid on shaft resistance was further examined in Fig. 11 using the peak shaft resistance values, i.e., $(f_s)_{peak}$, together with those normalized by the seawater case with $h_{ex} = 0\,h$, i.e., $\left(\frac{f_s}{f_s^{sw}}\right)_{peak}$ for all ground types considered. Note that the shaft resistance values are related to the square root of exposure time, i.e., $\sqrt{h_{ex}}$, as the linear relationship can be established between the two when using the square root of the exposure time as shown in Fig. 12. As can be seen in Fig. 12(a), $(f_s)_{peak}$ decreased almost linearly with square root of exposure time $\sqrt{h_{ex}}$, suggesting a strong dependency of shaft resistance to the exposure time of polymer fluid to the side wall of borehole. When plotting the normalized values $\left(\frac{f_s}{f_s^{sw}}\right)_{peak}$ against $\sqrt{h_{ex}}$ as shown in Fig. 12(b), $\left(\frac{f_s}{f_s^{sw}}\right)_{peak}$ for sandy gravel and jointed rock seems to decrease with $\sqrt{h_{ex}}$ at a much faster rate than sand, suggesting a greater time dependent effect of polymer fluid on bored piles installed in sandy gravel and jointed rock than in sand. For example, when installed in sandy



(a) $(f_s)_{peak}$



(b) $(f_s/f_s^{sw})_{peak}$

Fig. 12 Variations of peak shaft resistance $(f_s)_{peak}$ with $\sqrt{h_{ex}}$

gravel and joined rock an increase of h_{ex} from 0 to 24 h resulted in a 30% reduction in unit shaft resistance as opposed to 12% for sand. The best approximation of the given set of data could be made using linear equations with the parameters given in Fig. 12(b). Note that although not all fitting lines for different ground types intersect at exactly 1.0 for the y-intercept (b value in the equation), $b = 1.0$ can be used for all practical purpose.

These results confirm that in the event of a long delay between borehole formation and concreting for pile casting, polymer fluid may reduce shaft resistance of bored piles installed in sandy gravel and jointed rock under offshore construction environment. The potential adverse effect of polymer fluid on shaft resistance of bored piles however can be avoided by placement of concrete within 2-3 hours after the borehole excavation is completed.

4. Conclusions

In this paper, the results of an experimental investigation into the effect of polymer support fluid on shaft resistance of bored piles installed under offshore construction environment are presented. A series of pullout tests were performed on bored piles considering different types of support fluids and grounds and a range of support fluid exposure times using a model test setup that can simulate offshore bored pile construction process. Based on the results of the experimental study, the following conclusions can be drawn.

- Both the polymer and bentonite support fluids resulted in decreases in the shaft resistance of bored piles when installed under offshore construction environment. The decrease in the shaft resistance for the polymer fluid was, however, considerably smaller than for the bentonite fluid for a given exposure time. The lubricating effect of the slimy texture polymer on the concrete surface was the main cause for the decrease in the shaft resistance of bored pile with the polymer fluid, not by filter cake formation.
- The pullout resistance of a bored pile was affected by polymer type and its dosage. Although further studies are required to draw a general conclusion, such results highlight the importance of considering polymer type and its dosage in view of maximizing the load transfer characteristics of bored piles.
- A decreasing trend of shaft resistance with increasing the exposure time was evident in all types of grounds considered when using polymer fluid. The largest reduction in the unit shaft friction $(f_s/f_s^{sw})_{peak}$ of 30% was observed in sandy gravel, followed by 25% in jointed rock and 12% in sand for an exposure time of 24 h. When keeping the exposure time less than 2 to 3 hours, the effect was minimal to negligible.
- The results of the current study showed that polymer support fluid could adversely affect the shaft resistance of offshore bored piles, unlike those installed onshore. Differences in the groundwater chemistry between offshore and onshore piling could be the main cause for such discrepancy. Similar to the onshore construction, the adverse effect of polymer fluid can be minimized by avoiding a long delay between boring and concreting. Further studies are warranted to confirm the findings.

Acknowledgments

This research was supported by the National Research Foundation of Korea (Project Number: NRF-2021R1A2C3011490) and Hyundai Heavy Industries Co., LTD. This financial support is gratefully acknowledged.

References

American Petroleum institute. (2003), Recommended Practice for Field Testing Water-Based Drilling Fluids, API RP 13B-1/ISO 10414-1, 82. 3rd Ed., Washington, D.C: American Petroleum Institute.

ASTM D2487-11 (2011), Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System); West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D2487-17.

ASTM D3689 / D3689M-07 (2013), Standard Test Methods for Deep Foundations Under Static Axial Tensile Load; West Conshohocken, PA: ASTM International. https://doi.org/10.1520/D3689_D3689M-07R13E01.

Ata, A. and O'Neill, M.W. (1997), "Characterization of the effect of polybore TMP polymer on the construction and performance of drilled shaft foundations", Research Report; University of Houston, Houston, Texas, USA.

Brown, D. (2002), "Effect of construction on axial capacity of drilled foundations in piedmont soils", *J. Geotech. Geoenviron. Eng.,* **128**(12), 967-973. https://doi.org/10.1061/(ASCE)1090-0241(2002)128:12(967).

Brown, D.A., Turner, J.P. and Castelli, R.J. (2010), "Drilled shafts: Construction procedures and LRFD design methods", FHWA-NHI-10-016, Federal Highway Administration, Virginia, USA.

Camp, W.A., Brown, D.A. and Mayne, P.W. (2002), "Construction methods effects on drilled shaft axial performance deep foundations", *Geotechnical Special Publication No. 116,* ASCE, GSP 116, 193-208. https://doi.org/10.1061/40601(256)14.

Cernak, B. (1976), "The time effect of suspension on the behavior of piers", *Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering*, Vienna, Austria, January.

Cooke, R.W. (1979), "Load transfer from bored, cast-in-situ piles in London clay", *Behavior of Deep Foundations*, Philadelphia, USA, 250-263.

Farmer, I.W. and Goldberger, M. (1969), "Effect of bentonite on the skin friction of bored piles", Internal Report, Cementation Research, Ltd.

Fleming, W.K. and Sliwinski, Z.J. (1977), "The use and influence of bentonite in bored pile construction", Report No. PG3; Construction Industry Research and Industry Association, London, UK.

Frizzi, R.P., Meyer, M.E. and Zhou, L. (2004), "Full scale field performance of drilled shafts constructed utilizing bentonite and polymer slurries", *Geo-Support 2004*, ASCE GSP 124, 573-586. https://doi.org/10.1061/40713(2004)39.

Hsiao, C.C., Topacio, A.J. and Chen, Y.J. (2020), "Evaluation of side resistance for drilled shafts in rock sections", *Geomech. Eng.*, **21**(6), 503-511. http://dx.doi.org/10.12989/gae.2020.21.6.503.

ICE (Institution of Civil Engineers) (2016), *ICE Specification for Piling and Embedded Retaining Walls*, 3rd ed. ICE, London.

Iqbal, S., Jehan, B., Khan, F.A., Khan, H., Khan, S.A. (2019), "Assessment of roof waterproofing by pre-packaged polymer modified slurry (PPPMS) and bitumen", *Adv. Environ. Res.,* **8**(1), 71-84. https://doi.org/10.12989/aer.2019.8.1.071.

Lam, C. and Jefferis, S.A. (2015), "Physical properties of polymer support fluids in use and their measurement techniques", *Geotech. Test. J.*, **38**(7), 490–500. https://doi.org/10.1520/GTJ20140032.

Lam, C. and Jefferis, S.A. (2016), "Performance of bored piles constructed using polymer fluids: Lessons from European experience", *J. Perform. Constr. Fac.,* **30**(2). https://doi.org/10.1061/(ASCE)CF.1943-5509.0000756.

Lam, C., Jefferis, S.A. and Martin, C.M. (2014), "Effects of polymer and bentonite support fluids on concrete-sand interface shear strength", *Geotechnique*, **64**(1), 28-39. https://doi.org/10.1680/geot.13.P.012.

Lam, C., Jefferis, S.A., Suckling, T.P. and Troughton, V.M. (2015), "Effect of polymer and bentonite support fluids on the performance of bored piles", *Soils Found.,* **55**(6), 1487-1500. https://doi.org/10.1016/j.sandf.2015.10.013.

Majano, R.E. and O'Neill, M.W. (1993), "Effect of mineral and polymer slurries on perimeter load transfer in drilled shafts", Report UHCE 93-1; Dept. of Civil and Environmental Engineering, University of Houston, Houston, USA.

Majano, R.E., O'Neill, M.W. and Hassan, K.M. (1994), "Perimeter load transfer in model drilled shafts formed under slurry", *J. Geotech. Eng.*, **120**(12), 2136-2154. https://doi.org/10.1061/(ASCE)0733-9410(1994)120:12(2136).

Meyers, B. (1996), "A comparison of two shafts: Between polymer and bentonite slurry construction and between conventional and osterberg cell load testing", *Proceedings of the Southwest Regional FHWA Geotechnical Conference*, Little Rock, Arkansas.

Nash, K.L. (1974), "Stability of trenches filled with fluids", *J. Constr. Division*, **100**(4), 533-542. https://doi.org/10.1061/JCCEAZ.0000456.

O'Neill, M.W. and Hassan, K.H. (1994), "Drilled shafts: Effects of construction on performance and design criteria", *Proceedings of the International Conference on Design and Construction of Deep Foundations*, FHWA, Washington, D.C.

Wates, J.A. and Knight, K. (1975), "The effect of bentonite on the skin friction in case-in-place piles and diaphragm walls", *Proceedings of the 6th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, Durban, South Africa.

Yoo, C. (2017), "Performance of drilling fluids and their effects on RCD pile skin friction", Report SKKU-Geotech 17-1; Dept. of Civil and Environmental Engineering, Sungkyunkwan University, Suwon, Korea.

Yoo, C. and Han, Y.S. (2019), "Effect of drilling fluid on concrete-soil/rock interface shear strength in seawater drilling environment", *Mar.Georesour. Geotec.*, **37**(8), 936-944. https://doi.org/10.1080/1064119X.2018.1508259.

JS