Experimental investigation into the effects of polymer/bentonite support fluids on tensile shaft resistance of bored piles

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ABSTRACT: While synthetic polymer support fluids have emerged as alternatives to conventional bentonite support fluids in piling, their effects on the tensile shaft resistance of bored piles subjected to uplift loading are inadequately understood. In this study, two bored piles with designed length of 4.5 m and diameter of 300 mm were constructed using bentonite and polymer support fluids respectively, in a 5 m deep soil pit filled with uniformly compacted sand, at the National Buried Infrastructure Facility, NBIF. Their tensile performances were tested by loading upward axially and monitored by multiple embedded sensors including distributed fibre optics. Post-testing investigations on pile-soil interface characteristics were carried out by reconstructing digital profiles of the fully exposed concrete piles using 3D laser scanning. It was observed that with bentonite the pile developed a sand-clay filter cake layer, with an average thickness of 10.9 mm, which defined a cylindrical shear surface. In contrast, the polymer pile exhibited a rougher interface between the concrete and sand without filter cakes, with the failure surface represented by a cone of soil near the ground surface and a cylindrical shear below. It was demonstrated that, by using polymer support fluids, a stronger bond between the cast concrete and the surrounding soils was achieved, resulting in ~15% higher in ultimate tensile strength compared to that of the bentonite pile.

1 INTRODUCTION

Support fluids are crucial in maintaining borehole stability during the construction of bored piles by applying hydraulic pressure to prevent soil collapse before concreting. As alternatives to conventional clay suspensions support fluids, synthetic polymer support fluids have been used in bored pile construction since the early 1990s (Majano, 1992). Polymer fluid is an aqueous solution of long chain macromolecules composed of repeating monomer units, such as partially hydrolyzed polyacrylamides (PHPA). In contrast to the bentonite fluids, polymer fluids do not form a filter cake on the exposed borehole wall. As a water solution, polymer fluids do not suspend sand while drilling and therefore can be easily reused without a complex de-sanding process. These characteristics result in numerous operational benefits of polymer fluids compared to conventional bentonite fluids, such as smaller site footprints, ease of mixing and lower fluid disposal costs, all making the use of polymer fluids increasingly popular (Lam et al., 2014a; Lam and Jefferis, 2016). In recent years, utilising polymer support fluids for bored pile construction has become prevalent in several major infrastructure projects including High Speed Two

(HS2) (Tantivangphaisal et al., 2023) and the Gull Wing Bridge (Alex et al., 2023). In addition to these operational benefits, there has been much interest in understanding the mechanical influence of distinct support fluids on the engineering performance of bored piles due to different rheological properties and functioning mechanisms (Lam and Jefferis, 2016).

A range of small-scale laboratory tests have been previously conducted focusing on the concrete-fluid-soil interface behaviour. These demonstrated that bentonite support fluids led to a reduction in the concrete-sand interface shear strength due to the formation of a filter cake, whereas polymer support fluids could potentially promote stronger frictional resistance by preventing such formation (O'Neill et al., 1994; Lam et al., 2014b). According to several European case histories reported by Lam and Jefferis (2016), a thorough understanding of polymer fluid behaviour and its proper implementation are crucial for achieving excellent load-displacement characteristics of completed piles.

In practice, bored piles are also designed to carry tensile loads or up-lift forces in many cases, e.g. when they support high-rise towers subjected to wind load and underground structures subjected to buoyancy (Krabbenhoft et al. 2008; Chen and Chu, 2012; Ibrahim et al. 2017). In contrast to compression, when a bored pile is subjected to a tensile load, shaft friction is built up along the depth of pile-soil interface to resist upward motion. The mobilised tensile resistance depends mainly on the strength and stress states of soils around the pile interface, which can be reduced due to loosening effects and reduced confinement resulting from uplift (Kulhawy et al., 1979, Kulhawy, 1985).

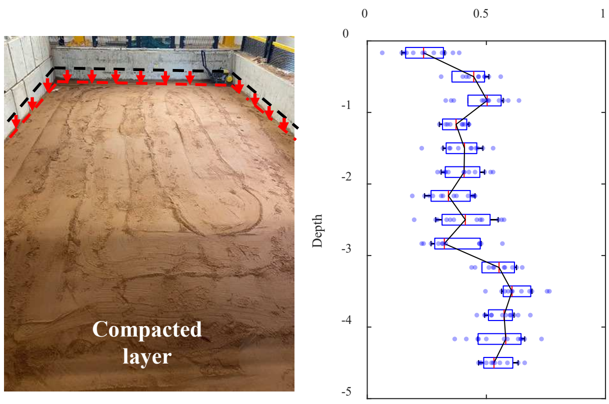
The existing research has primarily focused on examining the influence of polymer and bentonite support fluids on concrete-soil interface by modified direct shear tests coupled with field testing by compression load, although, these are often conducted with limited control over ground conditions. However, there is currently a lack of experimental studies investigating the effect of polymer and bentonite support fluids on tensile shaft resistance of bored pile, highlighting a significant gap in literature. In this paper, a comparative experimental investigation on tensile shaft resistance of bored piles constructed using bentonite and polymer support fluids respectively was performed in a controlled laboratory environment. This study, therefore, advances the understanding of the influence of the polymer and bentonite support fluids on the tensile shaft resistance of bored piles.

2 EXPERIMENTAL SETUPS

2.1 Test pit and soil properties

Tests were conducted in the National Buried Infrastructure Facility (NBIF) at the University of Birmingham. The test area was 5.7 m by 10 m in plan with a depth of 5 m. Gravelly sand was used in this experiment, comprising 20.8% gravel, 13.3% coarse sand, 40.5% medium sand, 23.4% fine sand. The sand, coefficient of uniformity (C_u) of 2.8, was classified as poorly graded, with minimum and maximum void ratios of 0.47 and 0.74 respectively, and the peak and residual friction angles measured dry as 46.3° and 36.6°, respectively.

The pit was filled using 15 compacted soil layers, as shown in Figure 1 (a). For each layer, the soil was first loosely placed in the pit and then compacted using a vibrating plate compactor to form an approximately 330 mm thick layer. Subsequently, the dry density was measured for each layer with the use of a nuclear density gauge at depths of 200 mm and 300 mm at 6 points per layer. The compacted layer and distribution of the density index of the backfilled soil along the depth is shown in Figure 1 (b). The level of variation in the measured density was controlled and expected to have limited influence on bentonite/polymer pile shaft resistance. The shaft resistance was mainly governed by the interface properties between the pile and soil, as discussed later in this paper.



(a) (b)

Figure 1. (a) Compacted soil layer, (b) soil density index along the depth, including the measurement points

2.2 Polymer and bentonite support fluids

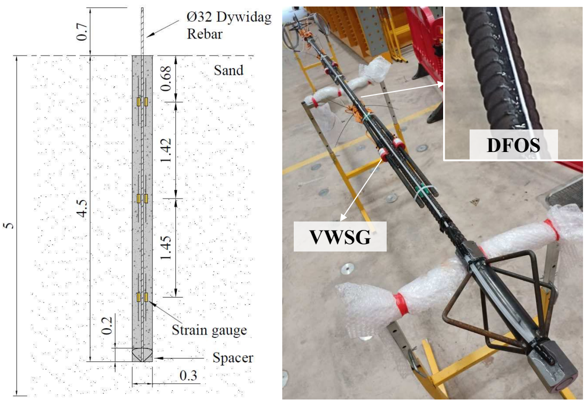
The bentonite support fluid was provided pre-mixed by Balfour Beatty with a density of 1.040 g/cm^3. The synthetic polymer support fluid was freshly mixed on site using SlurryPRO CDP provided by KB International, with a fluid density of 1.001 g/cm^3. The viscosities of the bentonite and polymer fluids, measured using the Marsh Funnel viscometer, were

40 s and 98~141 s, respectively. The construction of the piles was carried out by the Keller Group. Boreholes were drilled using a Hutte 203 Rig and remained open and supported with either bentonite or polymer fluids for a duration of up to between 22 to 23 hours. This allows a full comparison of the effect of the two support fluids on the borehole stability and pile shaft resistance under the same support durations.

2.3 Pile instrumentation and test execution

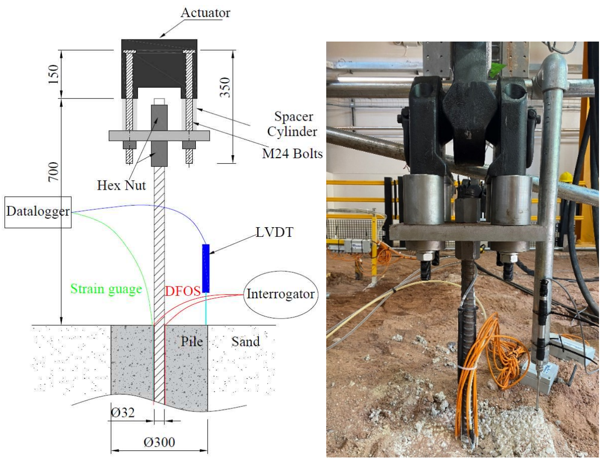
The bored piles were 4.5 m long and 300 mm in diameter, cast concrete, with a centrally embedded ϕ32 Dywidag rebar, as shown in Figure 2 (a). The piles were instrumented to fully capture their behaviour during the loading process. Six vibration wire strain gauges (VWSG) were installed in pairs for each pile on the Dywidag rebar to measure the tensile strains at three different depths. Two 4.3 m long distributed fibre optic sensors (DFOSs), manufactured by Nerve-Sensors, were mounted along the two sides of the Dywidag rebar to measure the distributed strain through the pile, as shown in Figure 2 (b). The gauge length of each DFOS was 2.6 mm.

Linear variable differential transformers (LVDT) were used to monitor the movement at the top of the pile, as shown in Figure 3 (a, b).



(a) (b)

Figure 2. Configuration and instrumentation of the testing pile, (a) dimension, (b) embedded Dywidag rebar with mounted VWSGs and DFOS



(a) (b)

Figure 3. Instrumentation and loading structure, (a) configuration and dimensions (b) bolted plate connecting structure between actuator and pile rebar

3 TEST RESULTS AND ANALYSIS

3.1 Piles' performance

A comparison of the load-displacement behaviour between the bentonite and polymer piles is presented in Figure 4. It is observed that both piles initially exhibited a similar load-displacement behaviour, characterised by high stiffness, with both piles exceeding 150 kN within the first 5 mm of head movement. Subsequently, the bentonite pile experienced a rapid yielding, reaching its peak load of 177.4 kN at 10.1 mm displacement.

In contrast, the polymer pile exhibited a more gradual and extended yielding process with slower stiffness degradation, achieving a maximum load of 203.3 kN at 13.8 mm displacement.

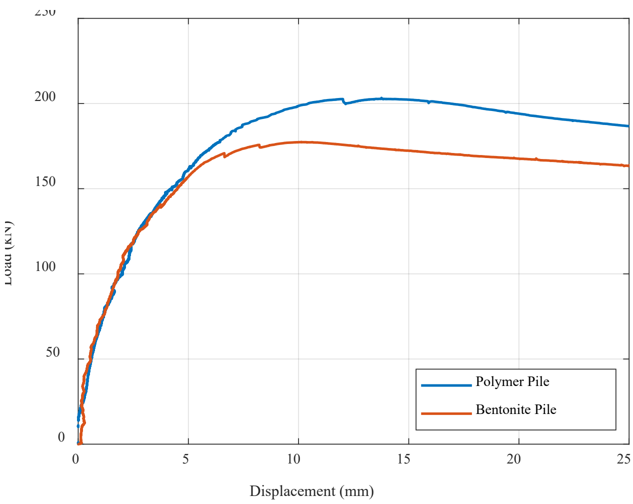


Figure 4. Load-displacement behaviour of polymer pile and bentonite pile

The soil surface around the heads of the bentonite pile and polymer pile after testing is shown in Figure 5. After the bentonite pile was pulled out, the surface soils around the pile head remained stable and undisturbed (Figure 5 (a)). In contrast, after the polymer pile was pulled out, visible radial direction cracks occurred in the soil, indicating shallow soil failure around the polymer pile (Figure 5 (b)).

(a) (b)

Figure 5. Pulled-out piles after testing and soil reaction in the surrounding area of the pile heads, (a) bentonite pile, (b) polymer pile

3.2 Distributed strain

The strain distribution along the piles was monitored using DFOS and VWSG, positioned along the rebar (see Figure 6). The strain measurements were compared at three loading stages (40 kN and 120 kN), for the polymer (Figure 6 (a) and (b)) and the bentonite piles (Figure 6 (c) and (d)). It is observed that DFOS strain measurements are in good agreement with VWSGs at different depths. To evaluate the difference between two parallel DFOSs at same load, the root mean square error normalised by the maximum measurement (NRMSE) of both sensors is calculated. It is found that the NRMSE is from 0.048 to 0.091, demonstrating good vertical alignment between the tensile force applied by the actuator and the pile central coordinates during loading.

For both piles, the distributed strain profiles indicate relatively higher strains in the upper sections of the pile, gradually decreasing with depth. This demonstrates effective pile-to-soil load transfer occurring predominately in the upper segment, consistent with typical pile behaviours under uplifting loading conditions (Meyerhof and Adams, 1968). As the applied load increased, strain values notably increased and extended deeper, reflecting progressive mobilisation and redistribution of shaft resistance along the pile length.

The distributed strain profiles of the polymer pile, as shown in Figure 6 (c~d), showed a significantly higher slope in the upper sections (-0.5 m~-2 m), compared to those in the bentonite pile as shown in Figure 6 (a~b). It became more pronounced as the applied load increased. This demonstrates a higher mobilisation of shaft resistance in the polymer pile, implying a stronger bonding interaction between the soil-concrete interfaces.

Considering the soil failure observed in Figure 5, the bentonite pile was pulled out along a cylindrical surface parallel to the pile-soil interface without disrupting the surrounding soil, demonstrating a pure frictional failure mode. In contrast, the polymer pile was pulled out with surrounding soil uplifted and radial soil cracks observed at the ground surface, demonstrating a composite failure incorporating both anchorage and frictional failure modes.

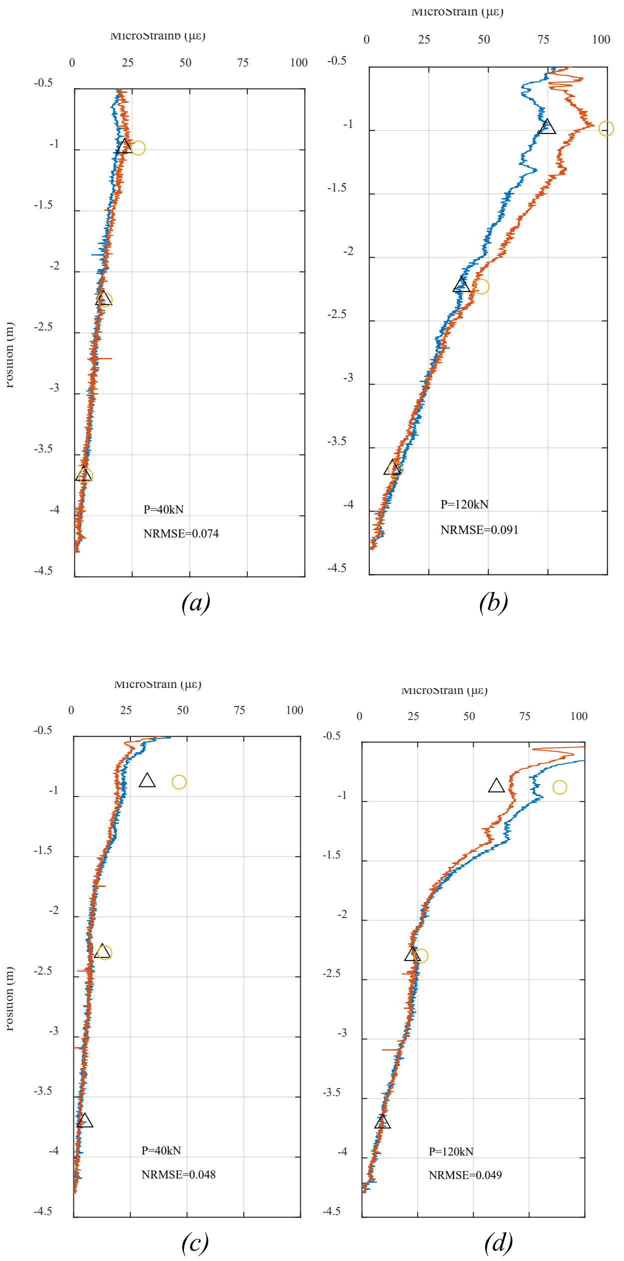


Figure 6. Pile strain under different load measured by DFOS and VWSG, (a) bentonite pile at 40 kN, (b) bentonite pile at 120 kN, (c) polymer pile at 40 kN, (d) polymer pile at 120 kN

4 INFLUENCE OF SUPPORT FLUIDS ON PILE-SOIL INTERFACE

4.1 Pile-soil interface observations

According to the analysis of the data obtained from the pullout tests on two piles, the polymer pile exhibited a significantly different behaviour compared to the bentonite pile, in terms of the distributed strains and load-displacement characteristics. The use of different support fluids during the drilling process directly influenced the pile-soil interaction mechanism, resulting in distinct soil failure modes around the piles. To better understand how polymer and bentonite support fluids influence the pile-soil interface, both concrete piles were fully exhumed after testing for further investigations.

Figure 7 presents photographs of the exposed surface of the bentonite (Figure 6 (a)) and polymer piles (Figure 6 (b)). For the bentonite pile, it was observed that the concrete pile was firmly covered by a sand-bentonite mixture layer, commonly referred to as a “filter cake”. The filter cake was intentionally removed to reveal the concrete surface of the pile shown in a square-shaped area at the centre of Figure 6 (a). Figure 7 (b) is the exposed surface of the polymer pile. It is observed that only a thin layer of loosely attached sand remained on the pile surface. In Figure 6 (b), the lower part displays the pile surface after excavation, with sand still attached, where the upper part is the exposed concrete surface after removal of the attached sand.

(a) (b)

Figure 7. Pile-soil interface observed after exhumation of, (a) bentonite pile, (b) polymer pile

When the bentonite support fluid is used during bore hole drilling in sand soils, the fluid tends to seep into the surrounding soils through the excavated bore hole wall due to hydraulic pressure differences. During this process, fine bentonite particles accumulate, bridging and clogging voids between large sand particles. This accumulation results in the formation of a low permeability sand-bentonite mixture layer, i.e., the filter cake. The filter cake layer cannot be effectively removed during the concreting process, it remained at the interface between the cast concrete and the surrounding soil, consequently resulting in a smoother pile-soil interface with relatively lower frictional resistance (Lam et al., 2014b).

When the polymer support fluid is employed in bore hole drilling, its higher viscosity and different rheological properties enabled it to stabilise the borehole without forming a distinct filter cake (Lam et al., 2014b). During concreting, the polymer fluid was sufficiently replaced by fresh concrete, resulting in direct contact between cast concrete and the surrounding soil. As a result, after concrete hardening, the polymer pile exhibited a rougher pile-soil interface compared to the pile constructed using the bentonite support fluid, which has been observed in Figure 7 (b).

4.2 Measurement of the filter cake thickness

Following observations on the exposed piles introduced in Section 4.1, 3D laser scanning was employed to reconstruct digital geometry profiles of the exposed pile surfaces. Each pile was scanned twice before and after the removal of the filter cake or attached soils with removal achieved using pressurised jet-washing. To accurately evaluate the apparent diameter of the pile and the filter cake, the thickness was obtained utilising point cloud data from 3D laser scanning. The following method is used in the paper.

A point cloud dataset P is obtained by 3D laser scanning,

$$P = \{p_i | p_i = (x_i, y_i, z_i), i = 1,2,3, \cdots, N\} \qquad (1)$$

where p_i represents a single point with three components (x_i, y_i, z_i) in the real-world coordinate frame, N represents total number of points

Next, the pile diameter at a certain depth h can be evaluated in $\{S\}$, find subset $P_h \subseteq P$ by equation (2):

$$P_h = \{p_j | p_j = (x_j, y_j, z_j), j \in [1, N], \|z_j - h\| \leq tol\} \qquad (2)$$

where tol is the tolerance. Therefore, the pile diameter d_h can be evaluated from the regression circle of P_h using the least-squares optimisation:

$$\min_{\xi_h, \eta_h, d_h} \sum_j \left(\sqrt{(x_j - \xi_h)^2 + (y_j - \eta_h)^2} - d_h/2 \right)^2 \qquad (3)$$

where (ξ_h, η_h) is the origin of the regression circle.

Figure 8 presents the PCD (point cloud data) profile of the bentonite pile according to 3D laser scanning, with the apparent pile diameter evaluated using the proposed algorithm. Figure 8 (a) shows the profile of the bentonite pile with the filter cake, while

Figure 8(b) shows its profile after the filter cake was removed. It is observed that the pile appeared more "slender" after removal of the attached filter cake, as expected.

Figure 9 illustrates the change in apparent diameters along its depth of the bentonite pile before and after jet-washing. The black curve corresponds to the pile before jet-washing, showing a larger apparent diameter due to the existence of the filter cake. The red curve represents the pile diameter after jet-washing, indicated a reduction in diameter as the filter cake was removed. The filter cake thickness was calculated according to the gap between the two curves, yielding an average value of 10.9 mm.

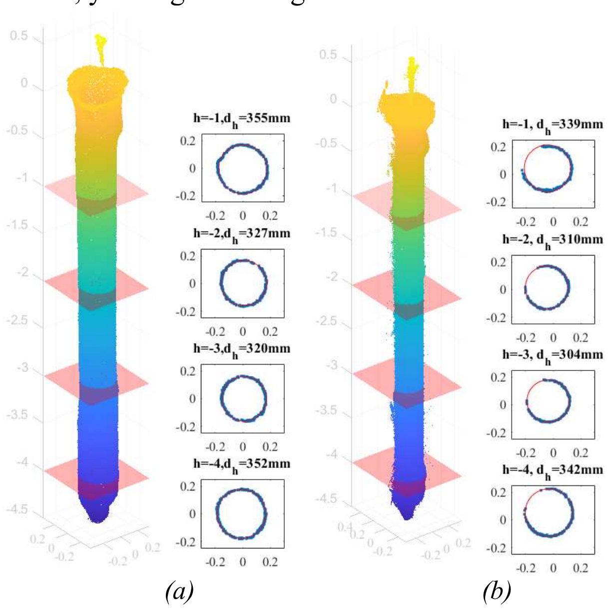


Figure 8. 3D laser scanning point cloud data of the bentonite pile, (a) pile profile with filter cake, (b) pile after removal of the filter cake

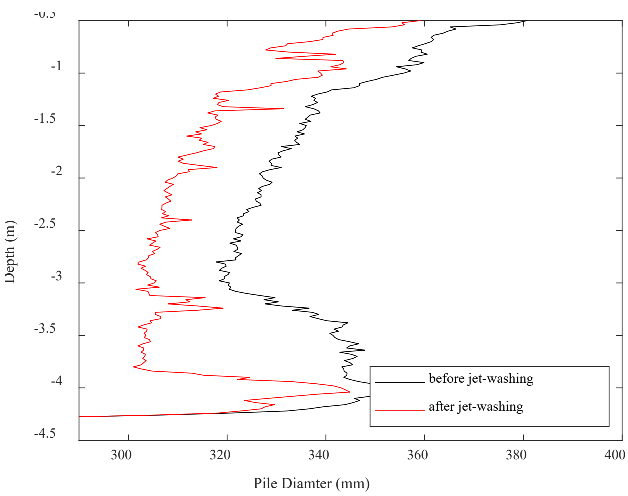


Figure 9. Apparent diameter of the bentonite pile before and after removal of the filter cake

Figure 10 shows point cloud data of the polymer pile and its apparent diameter at different depths. Figure 10 (a) shows the PCD profile of the exposed polymer pile, while Figure 10 (b) shows the PCD after removing the attached soil by jet-washing. It is observed that the pile surface became rougher after the soil was removed. Unlike the bentonite pile, which had a distinct filter cake, the polymer pile was covered only by a layer of loose sand rather than a well-formed filter cake. To quantify the thickness of attached sand, Figure 11 illustrates the change in apparent diameters along its depth of the polymer pile before and after jet-washing, where the gap between the black and red curves illustrates the thickness of the attached soil layer. The average thickness was evaluated as 5.5 mm.

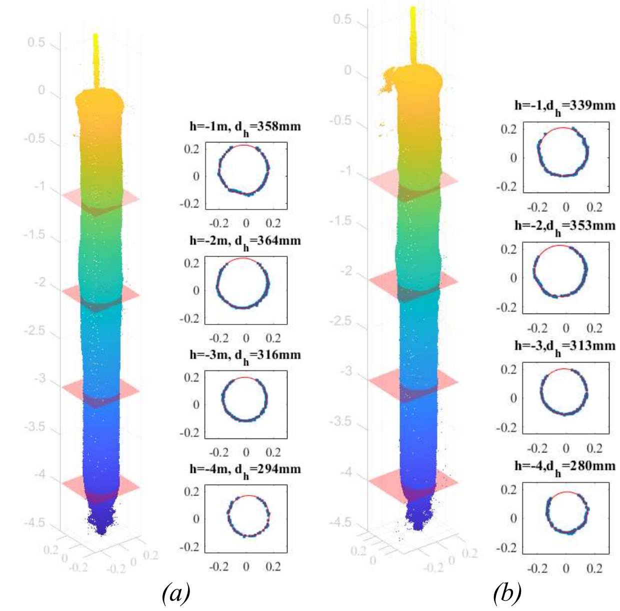


Figure 10. 3D laser scanning point cloud data of polymer pile, (a) pile profile with filter cake, (b) pile after removal of the filter cake

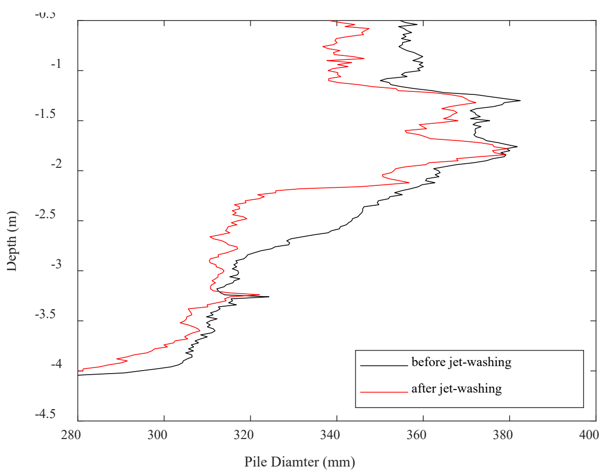


Figure 11. Apparent diameter of the polymer pile before and after removal of the surface soils

3D laser scanning results show that the bentonite pile developed a smoother concrete surface coated with a firm sand-clay filter cake with average thickness of 10.9 mm. The shaft resistance is mobilised along a cylindrical shear surface at the filter cake-soil interface. In contrast, the polymer pile exhibited a rougher concrete surface attached by a thinner loose sand layer with average thickness of 5.5 mm, which indicates a more complete bonding between the cast concrete and surrounding soil. The surface of the pile in polymer was less smooth, providing additional mechanical anchoring, this resulted ina higher tensile strength of polymer pile compared with the bentonite pile, as observed in Figure 4.

5 CONCLUSIONS

This study investigated the effects of polymer and bentonite support fluids on the tensile shaft resistance of bored piles through large-scale pull-out tests conducted under controlled laboratory conditions. Full-scale bored piles with a length of 4.5 m and a diameter of 300 mm were constructed using either polymer or bentonite support fluids and tested under axial tension force. From the instrumentation it was shown that both the bentonite and polymer piles exhibited similar load-displacement behaviour during the initial loading stage, with comparable responses up to 5 mm of pile head movement under 150 kN. Beyond that, the bentonite pile experienced a rapid yielding, reaching its peak load of 177.4 kN at 10.1 mm. In contrast, the polymer pile exhibited a more gradual and extended yielding process with slower stiffness degradation, achieving a maximum load of 203.3 kN at 13.8 mm.

For the first time in experimental investigations on bored piles, accurate measurements of the thickness of the filter cake along the shafts of full-scale bored piles were achieved. These measurements provide direct insight into the different working mechanisms of polymer and bentonite support fluids. The bentonite fluid stabilised the bore hole by forming a relative thick filter cake, with an average thickness of 10.9 mm, whereas the polymer support fluid was fully replaced by the tremie concrete without generating the filter cake. Instead, only a thin layer of loosely attached sand, with an average thickness of 5.5 mm, was observed. This results in a rougher concrete-soil interface and a more complete bonding interface, generating a component of anchoring. Consequently, under axial tensile loading, the polymer pile exhibited an ultimate tensile shaft resistance 14.6% higher than that of the bentonite pile. It is worth acknowledging that the conclusions drawn are limited by the small number of piles tested. More experiments are needed in future studies.

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