Performance of Bored Piles Constructed Using Polymer Fluids: Lessons from European Experience

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Abstract: Solutions of synthetic water-soluble polymers have been used for the construction of bored piles (drilled shafts) since the early 1990s. These engineered fluids are very different from conventional bentonite slurries but there is currently a serious lack of industry guidance. Despite their advantages over bentonite, performance issues have arisen in the past and foundation engineers remain wary of their use. To help practicing engineers avoid past pitfalls and to promote best practice, this paper presents a critical reappraisal of selected European case histories of bored piles constructed using polymer fluids. A collective reassessment is necessary in order to provide an overall picture of the situation as individual cases may show conflicting results. It is found that the completed piles can have excellent load–movement characteristics if polymer behavior is understood and respected. Conversely, excavation instability, structural defects, and poor pile performance can result if the special properties of these fluids are not fully appreciated and as a result they are not properly maintained. The findings presented in this paper will be useful for consultants and contractors when designing and constructing piles and diaphragm walls utilizing polymer fluids in the future. **DOI: 10.1061/(ASCE)CF.1943-5509.0000756.**

Author keywords: Bentonite; Bored piles; Case studies; Polymer.

Introduction

Since the pioneering work of Veder (1953), bored piles and diaphragm walls around the world have been regularly constructed using bentonite clay slurries to stabilize the excavations prior to concrete placement. A vast database of knowledge and experience with bentonite is now available and industry guidance and specifications exist [Federation of Piling Specialists (FPS) 2006]. However, since bentonite is a natural and finite resource and its use requires bulky ancillary plant for mixing and cleaning, foundation engineers have been in search of a more sustainable and better alternative for many years. Since the 1970s, solutions of natural polymers have been used sporadically in several countries but with mixed results partly due to their biodegradability. Natural polymers are still used today but are limited mainly to the construction of deep drainage trenches and permeable reactive barriers where biodegradation of the fluid is desirable (Day et al. 1999).

For the construction of deep foundations, the breakthrough came in the early 1990s when partially hydrolyzed polyacrylamides (PHPAs) were introduced to the construction industry by some material suppliers in the United States and their use has now spread from North America to other parts of the world. PHPAs are water-soluble synthetic polymers which carry a negative charge on the molecules. PHPAs now used in the foundation industry have a high molecular weight, so that when dissolved in water they form a non-Newtonian solution which may be used in replacement of bentonite slurry for excavation support. Unlike bentonite, polymer fluids do not form a gel when left undisturbed (nonthixotropic) and have negligible yield stress, although they can still have very high viscosity, up to 10^5 MPa · s at low shear rates (Lam et al. 2015). Polymer fluids have been found to offer many benefits such as smaller site footprint, ease of fluid mixing, and better concrete–sand interface resistance (Lennon et al. 2006; Lam et al. 2014a). However, since polymer fluids are very different from their bentonite counterparts both physically and chemically, their methods of use are also very different (Jefferis and Lam 2013; Lam et al. 2014b) and workmanship issues have arisen on some projects in the past (Berkovitz and Long 1995; Institution of Civil Engineers 2007). Therefore, despite the potential benefits many practicing engineers still remain wary of polymer use (Wheeler 2003). The current situation is also compounded by a lack of industry guidance and specifications. For example, ICE (2007) in the United Kingdom is silent on the required properties of polymer fluids although it specifies bentonite in detail. Similarly, the European standards on the construction of bored piles and diaphragm walls do not provide any guidance on the use of polymers although they are mentioned as a possible medium for excavation support [BS EN 1536 (BSI 2010a); BS EN 1538 (BSI 2010b)]. The same can be said for many other countries. In the United States, AASHTO (2010) gives some required properties for polymer fluids, specifying ranges for density, viscosity, pH, and sand content but the suggested lower and upper limits appear to have been directly transferred from material suppliers' recommendations. It is considered in this paper that these could be further developed.

To help develop guidance on polymer use, it is important to garner the experience available from published case histories, which are scattered through the literature and may also be written in languages other than English. To achieve this objective, a critical reappraisal of six selected European case histories has been conducted and the results summarized in this paper. The choice of this limited geographic area makes the task more manageable. Only case histories that contain a reasonable amount of site and construction information are included. In the subsequent sections, six different cases from the United Kingdom, Portugal, Italy, and Germany

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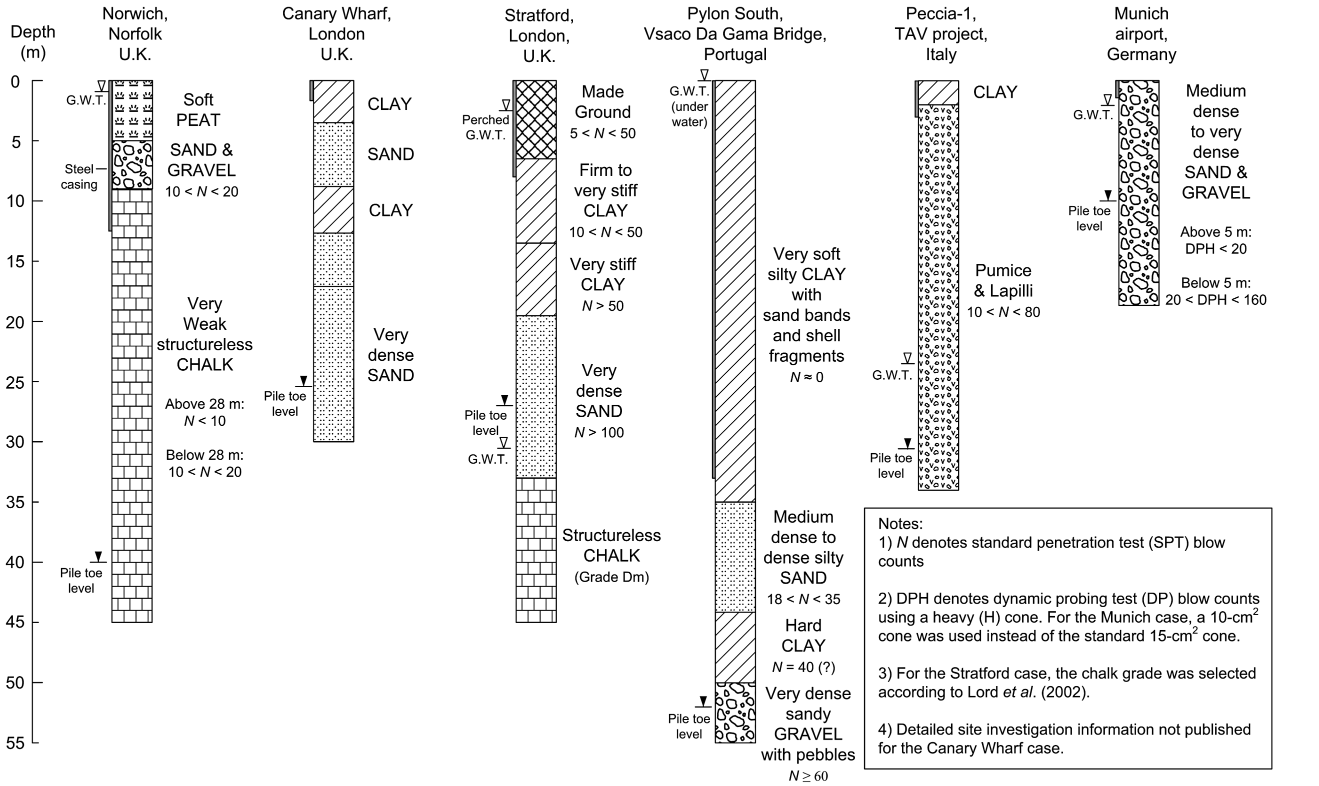

Fig. 1. Soil profiles, casing lengths, and pile toe levels at five European test sites

are discussed individually. During the discussions, the writers' views are offered to explain some of the highlighted (non)performance issues. To aid the subsequent discussions, Fig. 1 shows the soil profiles of the test sites that will be discussed.

United Kingdom

Piles in Chalk at Norwich, Norfolk

Corbet et al. (1991) reported what is possibly the first documented use of polymer fluids for the construction of bored piles. The site was the A47 Norwich Bypass in Norfolk, where the ground conditions consisted of 5 m of peat overlying 4 m of sand and gravel and then a very thick layer of weathered chalk. The ground water table was located near the surface (Fig. 1). The standard penetration test (SPT) blow count (N) ranged from less than 10 blows near the top to 20 blows at 45-m depth. The cone penetration test (CPT) cone resistance (q_c) ranged from 0.2 MPa at the top to 2 MPa at a depth of 32 m. Three 1.2-m diameter and 40-m long bored piles were constructed using three types of excavation-support fluids, as follows: (1) water (P1), (2) bentonite (P2), and (3) polymer (P3). Unfortunately, no detailed information about the fluids (e.g., type and viscosity) was given in the original publication. An inquiry was made to the original researcher (Mr. Steve Corbet of AECOM) but unfortunately the relevant records are no longer available.

After the excavations but before concreting, the side-wall profiles of the shafts were measured using a caliper. Fig. 2 shows the mean diameter of the shafts. The shaft supported by water had the roughest side-wall profile probably due to a local collapse, whereas the bentonite and polymer shafts were similar. The concreted volumes were 60, 52, and 54 m^3 for Piles P1–P3, respectively. Since the theoretical volume was only 51 m^3, Pile P1 can be said to have an overbreak of 18%, whereas for Piles P2 and P3 the amount of overbreak was much smaller at 2 and 6%, respectively. The large overbreak of Pile P1 paralleled the irregular profile of the shaft.

Fig. 3 shows the load–movement curves of the finished piles which were statically load tested. There are two aspects that are particularly worthy of discussion. First, although the water-supported shaft (Pile P1) had the most irregular side-wall profile

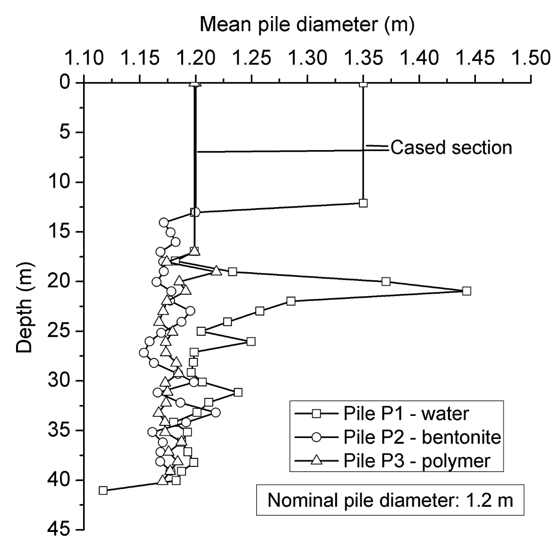

Fig. 2. Side-wall profiles of three test piles constructed using water, bentonite, and polymer support fluids at Norwich, United Kingdom (modified from Corbet et al. 1991)

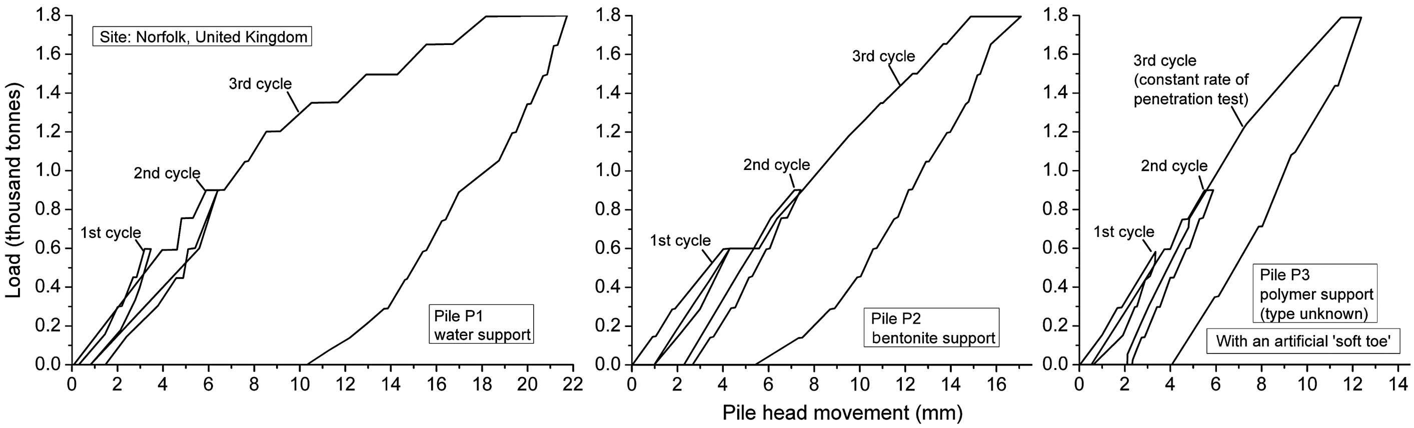

Fig. 3. Load–movement curves of three test piles constructed using water, bentonite, and polymer support fluids at Norwich, United Kingdom (modified from Corbet et al. 1991)

and the largest concreted volume (Fig. 2), as shown in Fig. 3 this pile still showed the largest settlement. This result was not expected by the original researchers as irregular side-wall profiles are commonly believed to lead to higher shaft resistances due to better interlocking between the pile concrete and the adjacent soil and rock. In the writers' opinion, what happened in the water-supported shaft was probably that, as water was unable to adequately stabilize the excavation, significant stress relief occurred in the soil which led to weakening and sloughing of the side walls and thus a lower shaft resistance.

Second, Fig. 3 shows that the pile formed under polymer fluid (Pile P3) significantly outperformed the other two in terms of load–settlement characteristics. This was despite the fact that Pile P3 was fitted with an artificial so-called soft toe made of polystyrene foam whereas the other two were not. The term soft toe is commonly used to describe a layer of soft sediment formed at the base of a pile which can be caused by insufficient base or fluid cleaning prior to concreting. A soft toe is undesirable but in this case it was artificially fitted to the pile excavated under polymer fluid (Pile P3) to remove the effect of base resistance on the overall response of the pile. The superior performance of Pile P3 indicates that the shaft resistance of this pile was very good and this was probably due to the successful stabilization of the pile bore during excavation as shown in Fig. 2. Currently, in the design of bored piles (drilled shafts) no differentiation is made between the different types of support fluid. This case study demonstrates that when polymer fluid is used better pile performance is possible.

Piles in Stiff Clay and Dense Sand in London: Case 1

There have been two separate studies that are concerned with the performance of bored piles constructed under polymer fluids in London, where the use of bentonite slurry is still the norm. The first is a case history reported in a professional news article by Wheeler (2003) who described a trial involving four test piles constructed using both polymer and bentonite fluids. Additional load test data has been obtained from the design consultant involved (D. Nicholson, unpublished presentation, April 2005). The test site, known as BP1, was located in Canary Wharf in East London, where the geological conditions consist of interbedded clay and sand layers from three different formations, as follows: (1) Lambeth Group (stiff clay and sand), (2) Harwich Formation (alluvial sand and gravel), and (3) Thanet Sand (very dense fine sand). The soil profile at one of the test pile locations (Pile TP2) is shown in Fig. 1. The groundwater conditions at this site, although not known to the writers, are believed to be similar to those described by Troughton (1992) for a nearby site.

The aim of the trial at Canary Wharf was to assess whether the pile design, which was carried out using empirical parameters developed for bentonite slurry, could be adapted to piles formed under polymer fluids. To this end, three 0.75-m diameter instrumented piles were excavated under polymer fluids [i.e., (1) Pile TP1, (2) Pile TP2, and (3) Pile TP2 R] and one was excavated under bentonite (Pile TP4). The polymer used was a PHPA marketed as CDP. To assess the effect of construction time, Pile TP1 was constructed over 37 h and the others in 12 h. All the piles were statically load tested to at least 220% of the design working load.

Fig. 4 shows the load–movement curves for the piles. The results offer useful insights into the behavior of piles formed under polymer fluids. First, the results showed that the measured resistances of all the piles were very good; they all equaled or exceeded the design values. Due to the high shaft resistances, there was little mobilization of pile base resistances and all piles failed structurally near the top rather than geotechnically. This finding reassured the design consultant that the use of polymer fluids did not lead to a reduction in pile shaft resistance, so that the existing design practice could be adopted for polymer fluids. Second, in terms of the possible effect of construction time, the pile constructed in 37 h was found to behave similarly to the other piles which were completed in 12 h. This finding led to the conclusion that the bores of the working piles (250 nos.), when formed under polymer fluid, could be left open overnight to allow better utilization of site resources. This decision was reported to have led to an increase in productivity of an extra half a pile per day because the contractor could start excavating a new pile bore in the afternoon and complete it the next day. This would not have been allowed if bentonite slurries were used since they are known to reduce pile shaft resistance with increasing construction time (Thasnanipan et al. 1998).

Piles in Stiff Clay and Dense Sand in London: Case 2

Lam et al. (2010) and Lam (2011) reported a similar comparative trial at Stratford in East London, where the ground conditions consisted of made ground overlying stiff sandy clay (Lambeth Group) and then very dense sand (Thanet Sand) as shown in Fig. 1. The purpose of the trial was to independently confirm the findings of the first East London trial, and also to assess the effect of polymer fluids on the quality of hardened concrete. To this end, three 1.2-m

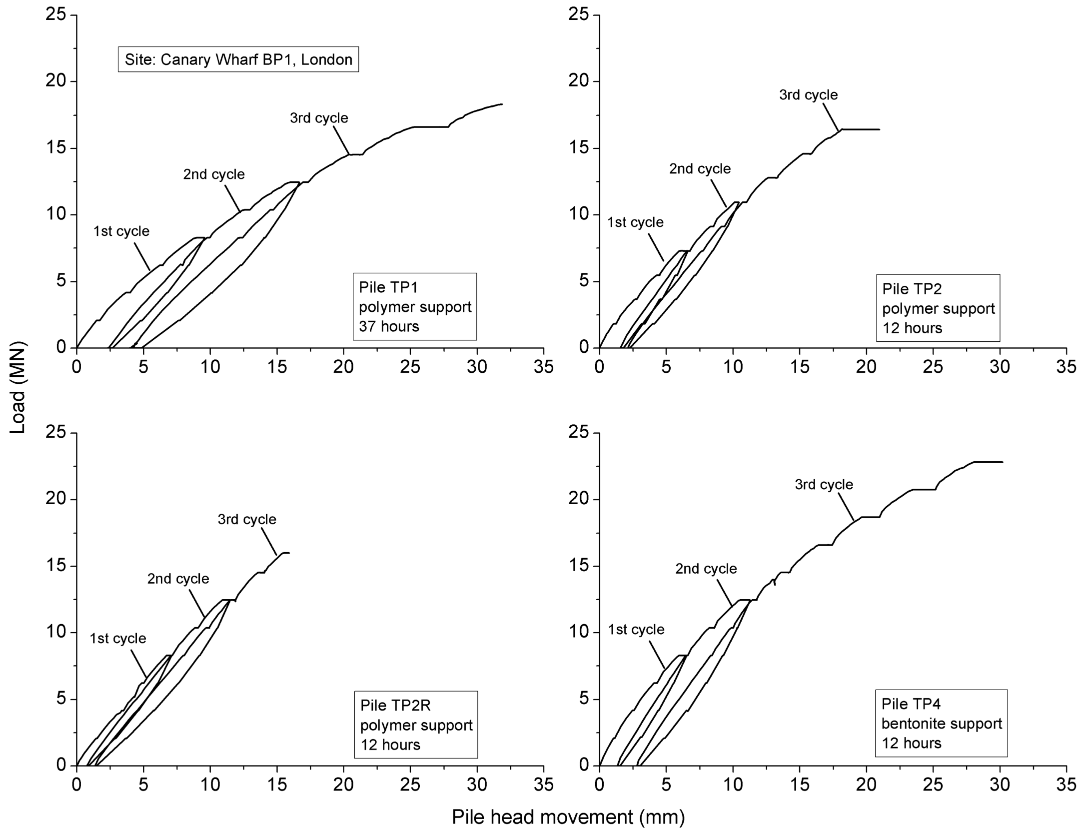

Fig. 4. Load–movement curves of four test piles constructed using bentonite and polymer support fluids at Canary Wharf in London, United Kingdom (data from D. Nicholson, personal communication, 2014)

diameter and 27-m long bored piles were constructed, two of which were excavated under polymer fluids [i.e., (1) Pile P1, and (2) Pile P2] and one under bentonite (Pile B1). The Marsh funnel viscosity of the support fluids, measured prior to use, were 70, 69, and 34 s for Piles P1, P2, and B1 respectively. The only difference between Piles P1 and P2 was their soil–fluid exposure time; the bore of Pile P1 was left open under fluid support for 7.5 h whereas Pile P2 was open for 26 h. The polymer product used was a PHPA marketed as CDP.

Fig. 5 shows the load–movement curves of the three piles which were tested to 18.1 MN which was twice the design working load. The head displacements under the maximum load were 51, 29, and 24 mm for Piles B1, P1, and P2 respectively. From the results, it can be concluded that Piles P1 and P2 significantly outperformed Pile B1, and that there was little difference between Piles P1 (7.5 h) and P2 (26 h). The reason why Pile P2 showed slightly less settlement than Pile P1 was probably due to the variation in the local ground conditions; note the center-to-center distance between the piles was 6 m. Nonetheless, these results confirm the findings of Wheeler (2003) that piles constructed using polymer fluids have good load–settlement characteristics and that increasing the construction time to two days has negligible effect on pile performance. This is possibly because of the ability of the polymer molecules to coat the exposed soil surface on the side walls and thus prevent the swelling of the soil. Fig. 6 illustrates this process by showing the interactions between polymer molecules and the clay soil in an excavation. Further details about the chemical interactions between polymer and clay soil can be found in Lam et al. (2014c) and are not repeated in this paper.

To assess the effect of the polymer fluid on concrete quality, during concrete placement samples were taken from the chute of the delivery truck and from the top of the concrete columns as it emerged from the bores of Piles B1 and P2. In a fluid-supported excavation, the top of the rising concrete column has the most exposure to the support fluid. Fig. 7 shows the strength and stiffness values of the concrete specimens plotted as a function of their age. Both bentonite and polymer fluids adversely affected the quality of the concrete by a similar degree. The reduction was probably

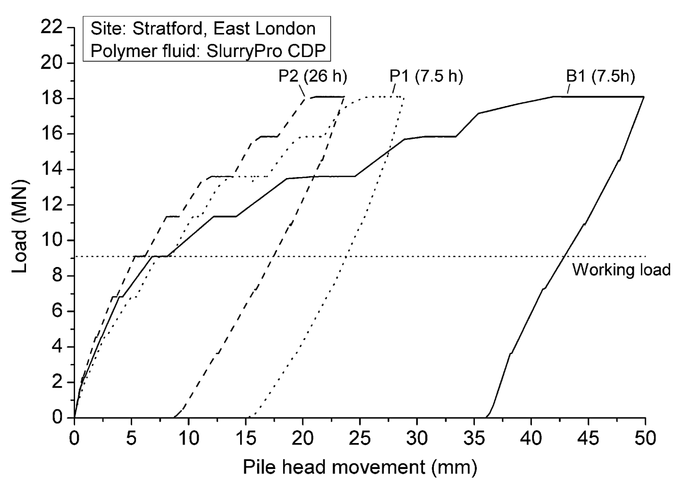

Fig. 5. Load–movement curves of three test piles constructed using bentonite and polymer fluids at Stratford, East London, United Kingdom; intermediate unload–reload curves are removed for clarity (adapted from Lam 2011)

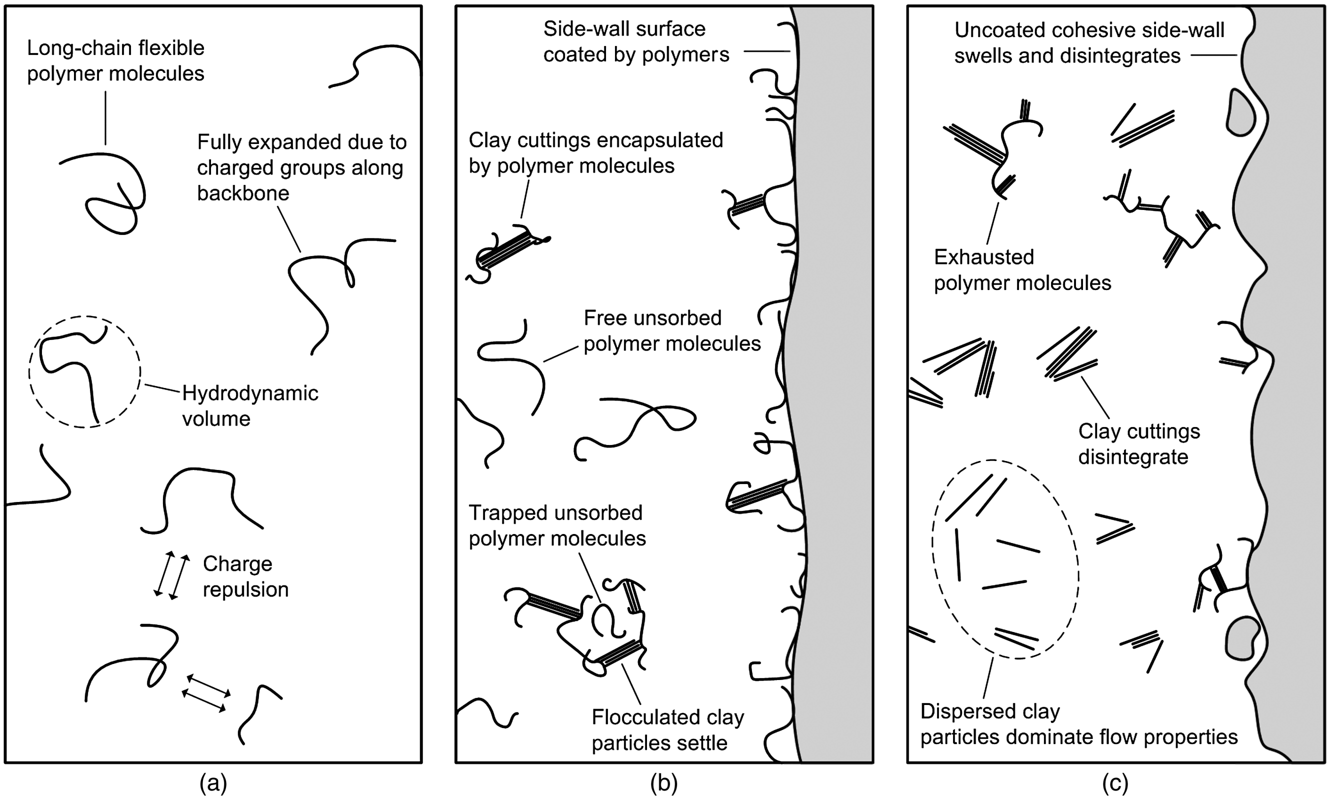

Fig. 6. Schematic interactions between polymer molecules and clay soil in an excavation supported by polymer fluids in different conditions (reprinted from Lam et al. 2014c, with permission; copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428)

caused by the increased water-to-cement ratio due to intermixing between the support fluids and the fresh concrete. In practice, the intermixed concrete can be removed by overpouring by a small amount and by trimming the pile head. This is a common practice for many contractors and in many countries. The test results show that the polymer fluid caused no more damage than bentonite and that the key issue is to always to minimize the intermixing of rising concrete and excavation fluid.

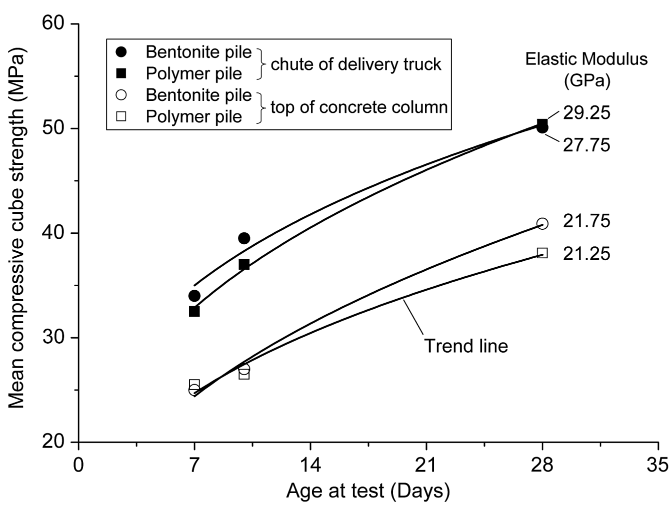

Fig. 7. Effect of bentonite and polymer support fluids on the compressive strength and stiffness of concrete (reprinted from Lam et al. 2010, with permission)

Portugal: Piles in Mixed Geology in Lisbon

Polymer fluids were used to construct the bored piles supporting the Vasco da Gama Bridge across the Tagus River in Lisbon. This project was documented by several teams of researchers including Bustamante et al. (1998), Sêco e Pinto and Oliveira (1998), Manuel Correia and Sêco e Pinto (1999), and Guadagnini (2001). Mr. G. Guadagnini provided additional information to the writers. As shown in Fig. 1, the ground conditions below the river bed consisted of 35 m of very soft silty clay (Layer 1), which was underlain by 9 m of medium dense to dense silty sands (Layer 2), 6 m of hard clay (Layer 3), and then at least 7 m of very dense sandy gravel with pebbles (Layer 4). The polymer used for this project was a high-molecular-weight PHPA marketed as Geomud-15. Brackish water from the Tagus River was used to mix the polymer at a concentration of 2 kg/m^3. The Marsh funnel viscosity of the fluid was 40 s. Although this viscosity value is rather low for PHPA polymers, it is within the expected range if brackish river water was used to prepare the fluids. The Marsh funnel efflux time for clean water is 26 ± 0.5 s.

Bustamante et al. (1998) and Guadagnini (2001) presented the load test result for a 1.2-m diameter instrumented pile constructed at the Pylon South (PS) location. This pile had a total length of 60.8 m, of which 52 m was embedded into the river bed. To evaluate the behavior of base (toe) grouting, after the first load test to 17.5 MN, the base of the pile was grouted in three stages (total injection volume 2,076 L) and the pile was tested again. Fig. 8 shows the load–movement curve. Base grouting caused in a much stiffer response and also probably a higher ultimate capacity. Stiff pile response was also observed in a trial in Taiwan where the pile was also constructed using polymer fluids and was base grouted in several stages (Duann et al. 2004).

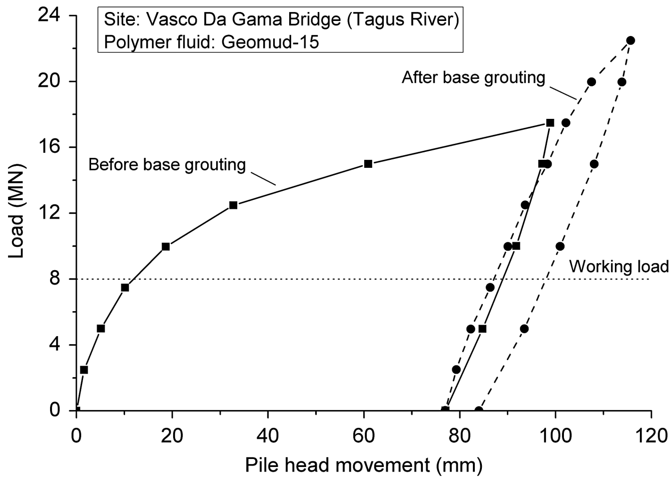

Fig. 8. Load–movement curve of a test pile constructed using polymer fluid at Pylon South, Vasco Da Gama Bridge, Portugal; intermediate unload–reload curves are removed for clarity (adapted from Guadagnini 2001)

From the load test results, ultimate unit shaft resistance (f_s) values were derived for each of the three soil layers and presented by Bustamante et al. (1998). By comparing these f_s values with those obtained from other sites, the original researchers concluded that polymer fluids did not lead to any reduction in shaft resistance, a finding that corresponds with the conclusions from the United Kingdom case histories discussed previously. Because of the satisfactory performance of the test pile, polymer fluids were allowed to be used for the construction of 278 working piles; these had larger diameters ranging from 2.0 to 2.2 m. At the time this paper was written, these piles are still some of the largest ever formed under polymer fluids. Another 548 working piles were also constructed using bentonite slurry by a different contractor. Of those piles formed under polymer fluids, three were found by sonic logging tests to have defects at the pile toes. This was equivalent to a defective rate of only 1%. This appears to suggest that polymer fluids do not adversely affect the structural integrity of piles.

Despite the encouraging experiences reported previously, a major problem was also encountered on this project; two of the working piles supported by the Geomud-15 fluid had to be redrilled using CDP polymer fluids. This was because the Geomud-15 fluid became contaminated with the in situ soil during excavation and lost its properties. The supplier of the CDP polymer noted that the Geomud-15 fluid was contaminated by the large amount of calcium and magnesium ions in the ground due to a nearby salt flats (KB Technologies 2000). The adverse effect of dissolved salts (cations) on the viscosity of PHPA polymer fluid was also observed by Schwarz and Lange (2004) in another piling project in Benin and by Jefferis and Lam (2013) in a laboratory trial. In the writers' opinion, the two collapses might have been prevented if (1) the Geomud-15 polymer fluid had been mixed at a higher concentration, or (2) potable water had been used rather than brackish waters to prevent the adverse effect of dissolved ions in the water; Point 2 also applies to bentonite slurry because dissolved salts can inhibit the dispersion of the bentonite (clay) particles (FPS 2006). To summarize, to avoid potential problems caused by fluid contamination, it is recommended that the salt contents of soils and pore waters are checked in advance when polymer fluids are proposed, if saline conditions are suspected. While on site, it would also be prudent to run the fluid at a concentration (viscosity) higher than would otherwise be required to create a buffer.

Italy: Piles in Pyroclastic Soil from Naples to Rome

Bustamante et al. (1998) reported on the piling works of the Naples–Rome section of the Italian high-speed train [Treno Alta Velocità (TAV)] project, for which a total of 1,732 bored piles were required to support the proposed viaducts. About half of piles were formed using bentonite slurries with the remainder under Geomud-15 polymer fluids. The polymer fluids were mixed at a concentration of 0.6 kg/m^3 which gave a Marsh funnel viscosity of 48 s. Compared to the Vasco da Gama Bridge project, the dosage of the polymer was lower but the viscosity was higher. This was probably due to the use of potable rather than brackish waters for mixing.

Two static pile tests were carried out [at the (1) Peccia-1, and (2) Cassino South-2 sites], where pyroclastic soil consisting of pumice and lapilli were present (Fig. 1). Pile 1 at Peccia-1 had a diameter of 1.2 m and a total length of 33 m. Fig. 9 shows the load test result. Due to the limited reaction load, the pile was tested only to 13.8 MN although the deduced ultimate capacity was over 20 MN. The derived unit shaft resistance (f_s) curves showed that, except near the pile top, the shaft resistance of this pile was not fully mobilized during the test so that the ultimate (highest possible) values were not achieved during the test. Pile 2, which was located at the Cassino South-2 site, also did not reach its ultimate resistance during the load test. Nevertheless, by comparing the mobilized f_s values with those obtained for continuous-flight-auger (CFA) piles from similar sites, the original researchers concluded that the polymer fluid did not lead to any reduction in shaft resistance in the pyroclastic soils. This conclusion is in line with the results from the United Kingdom and Portuguese cases described previously.

Following the satisfactory load test results, polymer fluids were used to construct the working piles at eight viaduct sites, all of which were sited on pyroclastic grounds. A total of 951 piles with a diameter of 1.2 m and up to 42-m deep were constructed. However, it was reported that at one site (Pisciarello) bentonite fluids had to be used instead due to the markedly cohesionless nature of the soil. In the writers' opinion, this was probably due to the relatively low Marsh funnel time of the polymer fluids used (48 s) as for PHPA polymer a funnel time of 60 s is now the norm. If the fluid at the Pisciarello site had been mixed to a higher viscosity, the use of bentonite might not have been necessary.

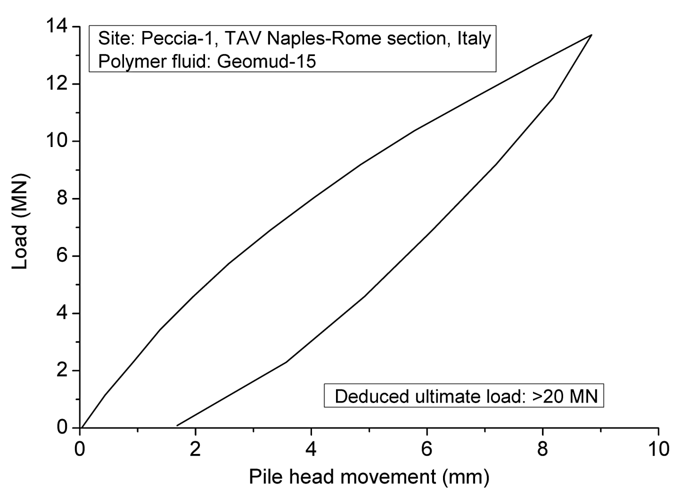

Fig. 9. Load–movement curve of a test pile constructed using polymer fluid at Peccia-1, Treno Alta Velocità project, Naples–Rome section, Italy (adapted from Bustamante et al. 1998)

Based on the results of structural integrity tests conducted on the completed working piles, it was revealed that about 10% of the piles had minor defects at the toes, although none required any repair work. This defective rate is significantly higher than that reported in the Vasco da Gama Bridge project although the defects were more minor. Although the original researchers did not explain the cause of the defects, the writers consider that the defects possibly may have been due to sediment accumulating at the base of the bores over the period from the end of excavation to the first pour of concrete. Unlike bentonite, polymer fluids have a negligible yield stress so that they cannot effectively hold soil particles in suspension. Careful cleaning of the used fluids and of the pile bases thus becomes extremely important when polymer fluids are used. Any sediment that is left at the base of a pile bore may not be displaced during casting. To further analyze the development of defects, it would have been useful to have had more information on the base and fluid cleaning procedures adopted by the contractors.

Germany: Piles in Sand–Gravel Mixture in Munich

Lesemann (2010) reported a field trial near the Munich Airport in Germany. The ground conditions consist of sand and gravel mixtures with an average permeability (k) of approximately 5×10^{-3} m/s. The ground water table was located near the surface (Fig. 1). The trial was conducted to assess the performance of polymer fluids in highly permeable coarse grounds. To this end, six 0.6-m diameter bored piles (Piles P1–P6) with a length of 10 m were constructed. Three types of polymer, namely (1) polyacrylamide (PAA), (2) carboxymethyl cellulose (CAM), and (3) XAN xanthan gum (XAM), were used for the trial. Bentonite slurry was also used to construct a pile for comparison. Table 1 summarizes the support fluid information for each pile.

To assess the stability of the pile bores, profiling of the side walls was carried out using the ultrasonic technique after excavation. Negligible difference was found between the side-wall profiles of the piles. This finding disproves the common perception that only bentonite slurry can stabilize excavations in gravely soil due to its ability to seal the surface by forming a layer of filter cake. As mentioned previously, polymer fluids were also successfully used to stabilize a sandy gravel layer with pebbles for the Vasco da Gama Bridge project. These experiences demonstrate that a layer of filter cake is unlikely to be a prerequisite for a stable fluid-supported excavation. For polymer fluids, the key is probably sufficient viscosity coupled with clogging of the coarser soil pores with the finer excavated materials. If fluid viscosity is not maintained due to salt contamination or other reasons, the stability of an excavation may deteriorate as previously shown by the bore collapse at the Vasco da Gama Bridge site.

After the construction of the test piles, Piles P3 (bentonite at 50 kg/m^3) and P4 (XAN at 2 kg/m^3) were load tested in compression using the other four piles to provide the reaction (tension) forces. Fig. 10 shows the load–movement curves for the six piles. Although the performance of both compression piles exceeded expectations, Pile P3 settled 10 mm less than Pile P4 did under the maximum load of about 5 MN. This finding is contrary to those obtained from the other case histories discussed previously, which all showed better pile performance when polymer fluids were used. The reason why this was not the case was possibly due to the low polymer concentration used for Pile P4. Typically, for foundation drilling a concentration of 3 kg/m^3 would be used for a natural xanthan polymer (Beresford et al. 1989) whereas only 2 kg/m^3 was used for Pile P4. As a result, the Marsh funnel viscosity for Pile P4, which was 38 s, was the lowest among all the piles constructed under polymers (Table 1). The effect of polymer concentration can also be seen by comparing the load–movement curves of Piles P4 (tested in compression) and P6 (tested in tension), both of which were excavated under xanthan fluids but at different concentrations (2 and 4 kg/m^3, respectively). When the applied head load is small, the effect of pile base resistance is often small or negligible so the response of these two piles can be compared. Fig. 10 shows that the initial load–movement response of Pile P6 was much stiffer than that of Pile P4. This suggests better excavation support for the former, although the original researchers also cited a flaw in Pile P4 as a reason for its inferior performance.

Piles P1 and P2 are another pair that is worthy of discussion, as they are also excavated under the same type of polymer fluid (i.e., PAA) but at different concentrations (6 and 2 kg/m^3). As shown in Fig. 10, pile P1 showed much larger movement than Pile P2 although the former was excavated under higher concentration (viscosity) fluid. The inferior performance of Pile P1 can be explained by the fact that concreting of this pile was only successful at the third attempt when the support fluid was replaced with water. During the first two failed attempts, the pile bore was supported by high-viscosity polymer fluids (funnel viscosity, 190–288 s) and the tremied concrete stiffened prematurely. The original researchers postulated several reasons for the failed attempts including chemical interaction between the concrete and the high-viscosity fluid. In the light of this experience, it may be prudent not to use polymer fluids prepared at a very high concentration or viscosity. Jones and Holt (2004) also noted that polymer fluids with a viscosity of 60 s appeared to have less detrimental effect on rebar–concrete bond strength than polymer fluids with a viscosity of 100 s. To conclude, this German case history highlights the importance of selecting a suitable concentration for the particular type of polymer used.

Table 1. Summary of Support Fluid and Test Pile Information

Pile designation	Support fluid type[a]	Concentration (kg/m^3)	Marsh funnel viscosity range[b]	Loading direction	Maximum load (kN)	Pile movement under maximum load (mm)
P1[c]	PAA	6	190–288 (225)	Tension	2,475	−19.8
P2	PAA	2	60–67 (63)	Tension	2,460	−11.3
P3	Bentonite	50	32–33 (32)	Compression	4,950	15.5
P4	XAN	2	37–41 (38)	Compression	4,930	23.3
P5	CMC	4	49–55 (52)	Tension	2,475	−12.4
P6	XAN	4	48–52 (50)	Tension	2,460	−9.5

Note: Data from Lesemann (2010).
[a]CMC = carboxymethyl cellulose; PAA = anionic polyacrylamide (i.e., PHPA); XAN = xanthan gum.
[b]Figures within brackets are the average values.
[c]Concreting of Pile P1 was only successful at the third attempt when the support fluid was changed to water.

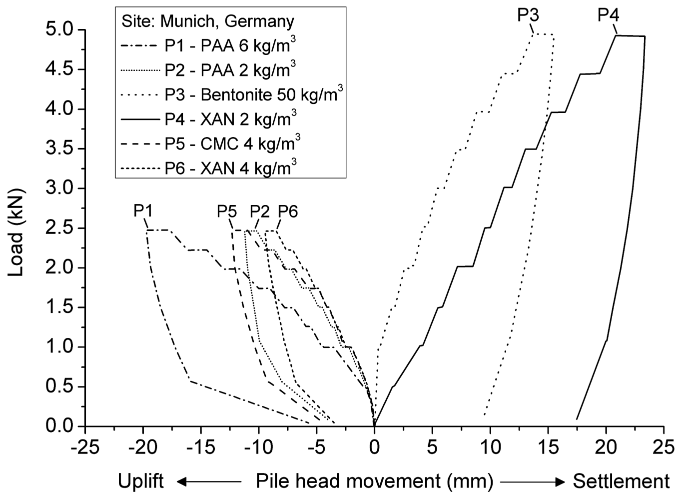

Fig. 10. Load–movement of six test piles constructed using bentonite and polymer fluids at Munich, Germany; intermediate unload–reload curves are removed for clarity (adapted from Lesemann 2010)

Too low or too high a polymer dosage is likely to cause problems or unsatisfactory performance.

Conclusions

The following conclusions can be drawn from the case histories examined in this paper.

Pile bore stability. The field experience gained in Norfolk, United Kingdom, suggests that water cannot provide adequate support to excavation in very weak chalk as shown by the irregular side-wall profile and large concrete overbreak. On the other hand, polymer fluids can stabilize such soils without problems. The German case history demonstrates that polymer fluids, despite having no gel and no ability to form filter cakes, can be successfully used in gravel–sand mixtures with an average permeability of 5×10^{-3} m/s. This finding challenges the common perception that only bentonite slurry can stabilize very coarse soil. The Italian case history also confirmed that polymer fluids can be used to stabilize coarse pyroclastic soils. In terms of excavation size, polymer fluids have been successfully used to support pile bores with a diameter of up to 2.2 m for the Vasco da Gama Bridge project in Portugal. However, collapses have also occurred twice there due to polymer contamination by salts in the ground. Together, these experiences show that polymer fluids are capable of supporting excavations in a wide range of ground conditions but care has to be taken to maintain the properties (including viscosity) of the fluids.

Marsh funnel viscosity. The previous discussions indicate that the chosen polymer concentration, and thus the viscosity of the polymer fluid, plays a substantial role in the successes and failures seen at the various sites. For the Portuguese and Italian sites, the PHPA (Geomud-15) polymer fluids were run at a Marsh funnel viscosity of 40 and 48 s, respectively, without major problems, although in the writers' opinion higher viscosity could have helped to prevent the collapses at the Portuguese site near the salt flats and avoided the use of bentonite at the Italian Pisciarello site. Equally, very high viscosity should also be avoided to prevent problems during concreting as shown in the German case. In the light of these experiences, until further evidence becomes available, contractors are advised to run PHPA polymer fluids a viscosity of at least 60 s but no higher than 100 s. This represents a tighter requirement than that currently recommended in AASHTO (2010) which specifies a viscosity range of between 32 and 135 s.

Concrete quality and structural integrity. The London Stratford case history has shown that there is little difference between bentonite and polymer fluids in terms of their effect on the quality of hardened concrete. Piles formed under polymer fluids have occasionally been found to have minor defects at the pile toes as shown by the Portuguese and the Italian cases. The writers note that defects can be formed if sediment is allowed to accumulate at the base of a pile during the period between end of excavation and the first pour of concrete, a period that can be up to several hours.

Pile performance. The experiences gained in Norfolk (chalk), East London (stiff clay and dense sand), Lisbon (mixed geology), and Italy (pyroclastic soil) all show that polymer fluids gave excellent load-movement characteristics to the completed piles. In addition, the two London case histories independently confirm that increasing the construction time to 26–37 h has negligible effect on the performance of the completed piles. This is possible because of the ability of polymer molecules to prevent the swelling of the clay soils. The German case history, however, shows that a pile formed under xanthan gum fluids settled slightly more than a similar pile formed under bentonite. This was believed to be caused by the low polymer concentration used (2 kg/m^3) as the typical dosage for this polymer type is around 3 kg/m^3.

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