Polymer Slurry in Foundation Construction

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A common method of constructing foundations for bridges or tall buildings involves deep excavations in which steel reinforcement and fluid concrete are placed while in a submerged state below the ground water table. The excavation stability is achieved by maintaining the fluid level of slurry within the excavation well above the ground water table and thus pushes outward against the soil side walls. The most common slurry products are comprised of clay minerals mixed with water to form a thick consistency capable of suspending soil cuttings. More recently, highly engineered polymer slurry products have emerged that, if used properly, far out-perform the traditional mineral slurry products. This paper outlines test results showing the marked performance improvements. Results from concrete to soil bond, steel reinforcement to concrete bond, and corrosion durability tests are presented from multiple research projects all coming to the same conclusion: present methods that use mineral slurry may be unwittingly constructing poor foundation elements, and polymer slurry alternates result in superior end products.

Introduction

Since the 1930's, mineral slurries have been used as the primary means of excavation stabilization in drilling applications [**1**]. These clay solutions have a density that is both higher than the surrounding ground water and have a gel strength sufficient to suspend soil particles making them ideal to stabilize open excavations. The extension of mineral slurries seemed to be an obvious choice for use in the construction of deep foundations and its use went unquestioned. However, recent studies [**2-5**] indicate the method of concreting, when below the water table, creates a concrete flow pattern that traps slurry on the back side of the steel reinforcement required to strengthen the foundation element. In some cases, radially projected creases extend to the shaft surface. The highly viscous, particulate laden consistency of mineral slurry means that small amounts of trapped material can have a lasting impact on the concrete to steel bond strength, concrete to soil shear capacity and durability of the affected structure. The emergence of highly engineered polymer slurries mitigates these issues to a large degree. These proprietary blends of partially hydrolyzed polyacrymalides have been shown to out-perform mineral slurries in every aspect of performance tested [**3-5**].

This paper discusses the results of three previous studies wherein the effect of slurry type was assessed for a specific structural parameter: (1) concrete to soil shear strength called side shear, (2) concrete to steel bond or rebar pullout capacity, and (3) durability stemming from corrosion resistance [**3-5**].

Background

The category of deep foundations most affected by slurry usage are cast-in-place concrete elements. The most common in this category is the drilled shaft (also known as bored piles or cast-in-drilled-hole piles). These elements are prism-shaped cylinders and are chosen over other foundation options due to their relatively small footprint, straightforward construction process, and ability to withstand large axial and lateral loads. Drilled shaft construction is most commonly performed below the water table (**Fig. 1**) and as such maintaining excavation / soil side wall stability is critical. Stability is achieved by maintaining a level of slurry within the excavation a minimum of four feet (1.2m) above the ground water table [**6**]. Thereby, a net outward pressure results from the higher fluid level and increased fluid density that prohibits the inflow of ground water and prevents side wall sloughing.

Typical products used to form drilling slurry are bentonite, attapulgite or other clay minerals (mineral slurry), and synthetic polymer compounds sold in dry or emulsified forms (polymer slurry). Both slurry types must be mixed with water prior to introduction into the excavation. The mixing process and concentration is specific to the type of slurry used and must be strictly followed to achieve the desired slurry properties.

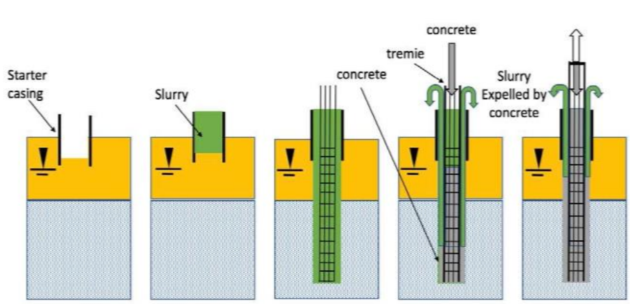

Fig. 1. Steps in the construction of drilled shafts [6].

During the drilling process, slurry is continually placed in the open excavation. The high viscosity of the slurry minimizes inflow into the surrounding soil and allows the fluid level to be built up in the excavation prior to removing large volumes of excavated material. In this way, the slurry level can always stay higher than the ground water even when an immediate drop in level occurs from the removed soil.

Upon successful excavation and with the side walls stabilized by the slurry, a full length steel reinforcing cage is lowered into place followed by a tremie pipe or a rigid concrete pump line which must extend to the bottom of the excavation. Concrete is then placed via the tremie pipe and the concrete level builds up within the reinforcing cage displacing the slurry as it rises. There is a common misconception that concreting displaces slurry like oil over water, rising with a constant, even level. In actuality concrete builds up inside the reinforcement cage pushing through radially into the surrounding annulus region trapping slurry during the displacement process (**Fig. 2**).

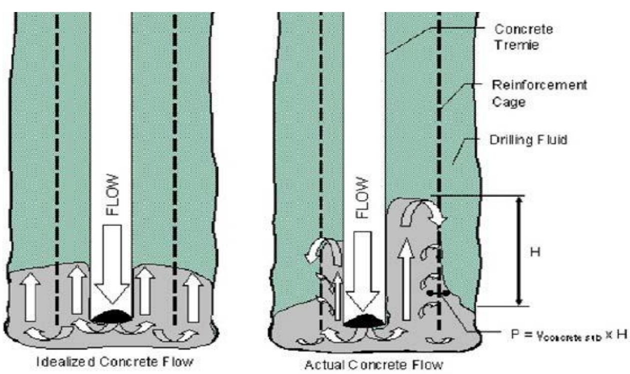

Fig. 2. Idealized and actual concrete flow patterns.

The concrete in the annulus, outside the reinforcing cage is the most import concrete in the entire foundation element as it forms the bond with the surrounding soil or rock, provides the most mechanical advantage to resist bending in the element and serves as the cover that protects the steel from corrosive exposures.

As concrete flows around the reinforcement bars, it is cleaved and then rejoins in the cover region of the shaft. This small detail affects all three structural concerns. First, as the concrete pushes out against the sidewall, slurry becomes trapped leaving a film on the concrete surface between the concrete and soil which negatively affects side shear resistance. Second, the slurry that coats the reinforcing steel prior to concreting is never completely removed. Trace amounts of slurry remain, separating the rebar from the concrete and preventing the proper development of bond strength. Third and finally, during the cleaving process, a small amount of slurry mixes with the concrete surface forming an interface. As the cleaved interfaces come back together in the cover region of the shaft, a slurry residue is left in the newly formed crease. This crease not only compromises the structural integrity of the cover region, but also creates a pathway for environmental chlorides to access the reinforcing steel, promoting premature corrosion. All of these structural concerns are realized when mineral slurry is used, but have proven to be negligible in cases where concrete displaces polymer slurry.

A brief description of three test programs is presented whereby the effects of slurry type on the soil interface, reinforcing steel interface and the cover protective properties where assessed.

Experimental programs

The work described herein was completed in three research projects conducted over a 5-year span. Full details on the experimental procedures can be found elsewhere [**3-5**].

Side shear program

As part of this research program, thirty-two, 1/10th scale (4in diameter [102mm]; 96in [2.44m] long) drilled shafts were cast and tested for side shear pullout resistance. All 32 shafts were constructed similarly, using a hand auger and where slurry was introduced when the excavation reached 1ft [0.3m] depth. After the excavation was completed, the slurry level was maintained for varied amounts of time ranging from 20min to 96hr. Concreting ensued via tremie placement and where slurry was displaced.

The pullout testing setup and procedure was the same for all 32 shafts, as described by Allen [**8**] and Caliari de Lima *et. al.*, [**9**]. The load was applied by positioning a hollow-core hydraulic jack over the threaded rod coming up from the shaft and up to a load frame; a 10 MT capacity hollow-core load cell was positioned on the top of the assembly and restrained by a steel plate and nut. A reference frame was positioned orthogonal to the reaction beam to avoid undesired effects of ground movement on displacement measurements and to which a displacement transducer was mounted. The data was recorded using an Omega Model USB OMB-55 data acquisition device, a field computer and a weather resistant enclosure [**3**]. A manually operated hydraulic pump was used to slowly apply and control jack pressurize. The loads were applied in increments of 500lbs [2.2kN], and each step was held for 2 min. After observing failure, the test was continued until the displacement transducer stroke was fully used (4in [102mm]). All pull-out tests were performed between 7 and 9 days after concreting.

Bond strength program

In all, 52 large scale shaft specimens were tremie-placed (slurry displaced) after the slurry and reinforcing cage were already in place. The shaft specimens were tailored to meet local minimum diameter and preferred tightest cage spacing criteria [6]. Specimens were 42in (1.07m) diameter, 24in (0.61m) tall, and were formed with a cylindrical steel sheet metal form. Rebar spacing resulted in 6in (152mm) clear spacing between both the longitudinal and circumferential steel and 6in (152mm) of cover / annulus region was provided between the rebar and the side of the shaft concrete. Longitudinal rebar for pullout specimens were position every other main bar and where pullout bars did not touch the steel stirrups. Outer steel stirrups were placed outside seven of the main bars that were not tested. One half inch (13mm) plastic hoops (simulated stirrups) were used to separate the inner and outer rings of main bars (**Fig. 3**). The inner 7 vertical bars / test specimens (#8 or M25 rebar) were tied inside the plastic hoops, but between the outer seven bars [**4**].

Fig. 3. Rebar pullout specimens: bentonite (left), polymer (right).

Pullout testing was completed similar to the side shear study using a manually operated hydraulic pump but in this case with a continuously increasing load (typical of concrete strength testing) at a rate of approximately 100lbs/sec (0.4kN/sec). The load cell and a displacement transducer were monitored with a computerized data acquisition system and sampled at 10Hz to capture the peak pullout force. The testing was performed after the concrete reached the target compressive strength of 4 ksi (28MPa). All pullout testing was completed on the same day as concrete strength testing. Of the 227 pullout tests, 131 were performed on mineral slurry cast specimens, 56 in polymer and 40 in water.

Corrosion resistance program

Using the same specimens described in the bond strength program (**Fig. 3**), the protection performance of the concrete cover was assessed. Therein, surface potential measurements were used. Surface potential measurements are a strong indicator of active corrosion within a reinforced concrete structure. This test is performed by measuring the relative voltage potential between the reinforcing steel and a copper-copper sulfate electrode in wetted contact with the concrete surface several inches away from the reinforcing steel [**5**]. When the measured potential is more negative than -350mV there is a high probability of corrosion [**10**].

The surface potential of each shaft specimen was mapped evenly over the surface using a prescribed grid layout. In all, each specimen was measured at 80 uniformly spaced locations. The shafts were wetted and surface potential testing was then conducted per ASTM C876-09: *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete* [**9**], using a copper-copper sulfate reference electrode and a standard multi-meter. While not presented, concrete resistivity has similar capabilities to determine how well the cover might protect the steel. Low resistivity implies poor protection and high resistivity indicates good isolation/protection. The presence of creases in the concrete shown in **Fig. 3** (left) provides direct electrical connectivity between the steel and the surrounding environment without the concrete barrier for protection. Note no creases were visible in the polymer cast specimens.

Results and discussion

Side shear tests

While the study focus was the effects of prolonged slurry exposure on side shear [**3**], it is clear that the three polymer slurry products (C, M, and K data markers in **Fig. 4**) gave higher side shear values regardless of exposure time relative to the bentonite exposed specimens (B). P denotes the average of all polymer cast shafts.

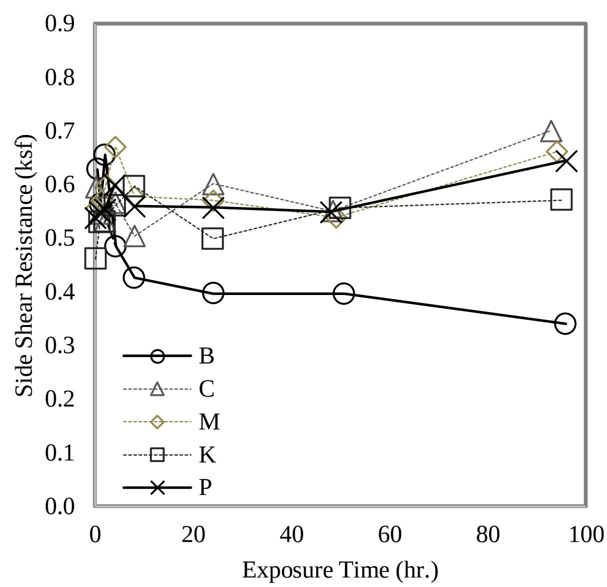

Fig. 4. Performance of polymer (CKM) and mineral slurry (B).

Similar results were shown in a companion study using full size shaft specimens exposed for up to 48 hrs. [**3**]. Overall, the polymer cast shafts performed 26% higher than the bentonite shafts and where no degradation with time was observed. In contrast, the bentonite shafts showed a sharp reduction in side shear over the first 8hrs but only modest reductions thereafter.

Bond strength tests

The reliability of structural performance for reinforced concrete structures is directly influenced by the measured to predicted strength ratio. Hence, a designer predicts the capacity of an element based on code specifications and best engineering practices and where the designer fully expects the actual load carried to be less than the predicted and/or measured strength. Therein, two types of safety are imparted into the design: carried load is less that predicted strength; and predicted strength is less than the actual or measured strength.

The measured/predicted capacity ratio for rebar cast in concrete in dry conditions and used in codes/design is shown in **Fig. 5** to be approximately 1.23 [**11**]. A ratio greater than 1.0 implies a conservative prediction. Ratios less than 1.0 indicate an unsafe design. To date, no consideration for concrete cast in slurry environments has been included in design specifications. The **Fig. 5** data shows a generally decreasing trend in the strength ratio with increasing slurry viscosity. The average of all water cast tested specimens was essentially the same as dry conditions used to generate current design prediction expressions [**11**]. However, when slurry products were introduced reductions in capacity followed. Use of bentonite slurry resulted in an average strength ratio of 0.8; polymer slurry was 1.0 which indicates a safe design but without the same safety margin as the code based predictions.

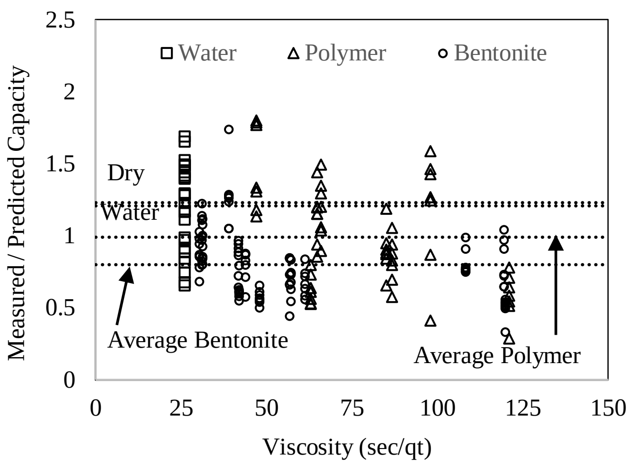

Fig. 5. Strength ratio versus slurry viscosity.

When further considering the effect of statistical variability (standard deviation) and not just the average, these results suggest the bond strength should be expected to be approximately half for bentonite casting conditions. Polymer slurry effects on bond, while less severe, will still require some reduction to be considered. This may depend on the exact polymer product used and where more or less reduction will result [**12**].

Corrosion resistance tests

The copper-copper sulfate testing for each shaft included 80 data points. The 50th percentile (E_{50}) potential value was determined for each shaft and where these values ranged from -508mV to -155mV when considering all shaft specimens. Thirty five percent of the shafts had E_{50} potentials below the -350mV threshold and all of those shafts were constructed using bentonite slurry. Surface potential contours for representative water, polymer and bentonite shafts are shown in **Fig. 6**.

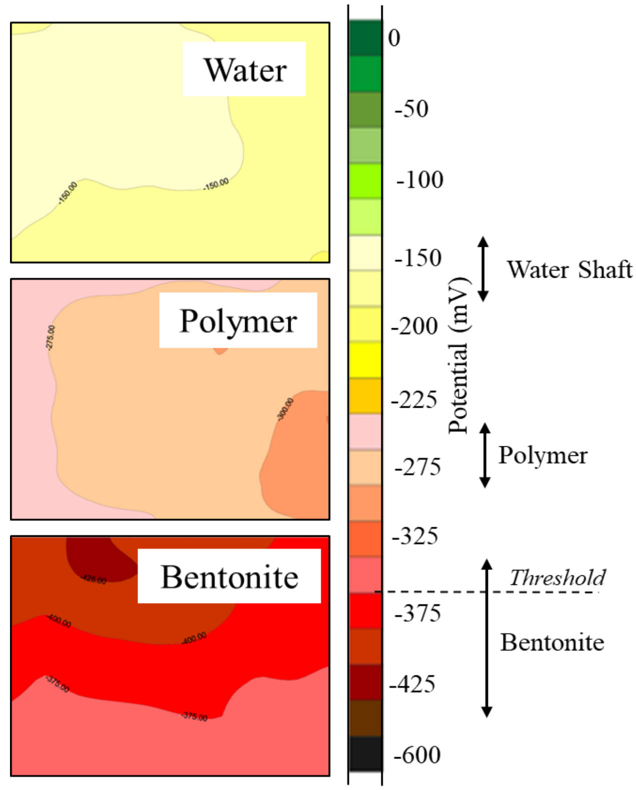

Fig. 6. Surface potential measurements (below -350 is corroding).

The range of surface potential values for each casting fluid environment are shown by the span of the arrow heads beside the contour plots. Both the water and polymer cast specimen values were safely above the -350mV threshold, water being slightly better than the polymer. The bentonite slurry cast specimens showed values to be largely below the threshold with only a few occurrences greater than -350mV. However, while few bentonite shafts had E_{50} values above the threshold, all bentonite specimens had at least one occurrence in the entire contour that fell below the safe no corrosion threshold.

Conclusion

Slurry is a requisite component of submerged drilled shaft construction. The results of the testing completed for the three research projects were presented and showed conclusively that polymer slurry has little or no adverse effects on the quality of the as-built drilled shaft. In contrast, the use of mineral slurry can have devastating results drastically reducing the expected lifespan and strength of the structure.

Continued work

Diving operations are underway to further confirm the findings of this work where the corrosion protection of in-service bridges is being assessed. Future tasks include full-scale testing and continued corrosion monitoring.

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Author's contributions

Conceived the plan: GM, SM, KC; Performed the experiments: SM, KC; Data analysis: SM, KC, GM; Wrote the paper: SM, GM, KC. Authors have no competing financial interests.

Keywords

Bored pile, drilled shaft, corrosion durability, polymer slurry, rebar bond.

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