Reinforcing Bar Pullout Bond in Tremie-Placed Concrete Cast in Drilling Slurry Environments

by Kelly Costello, Sarah Mobley, Justin Bowen, and Gray Mullins

Drilling slurry made from a mixture of water and mineral or polymer powder is often used to stabilize deep excavations, in which cast-in-place reinforced concrete foundation elements such as drilled shafts are constructed. At the time of concreting, drilling slurry is displaced by heavier, highly fluid concrete tremie placed at the bottom of the excavation from within the reinforcement cage. Despite the fluidity of the concrete, it must build up within the reinforcing cage to a sufficient height before then radially pressing into the annular cover region. This flow pattern has been shown to trap slurry near the steel reinforcement and affect reinforcing bar bond. This paper presents the results of 227 reinforcing bar pullout tests performed over a 6-year period from 2012 to 2018. Shaft specimens were tremie placed in various slurry types and consistencies. This analysis concluded that present development length values should be increased by 1.8 for bentonite and 1.9 for polymer slurry; water casting environments showed no significant change relative to dry conditions.

Keywords: development length; drilled shaft; mineral; polymer; reinforcing bar bond; slurry.

INTRODUCTION

Drilled shafts (also known as bored piles or cast-in-drilled-hole piles) are large-diameter cast-in-place reinforced concrete foundation elements used to support bridges and tall buildings. Due to the axial and lateral capacity that can be developed, a single shaft can replace a group of smaller-sized driven piles. Structurally, the design of shafts uses the same resistance factors as their above ground reinforcement counterparts, which assumes the same level of quality assurance. This extends to those portions of the shaft below the water table where the cage is placed, and the concrete is tremie-placed under submerged conditions.

The two most common complications that arise during drilled shaft construction stem from: 1) excavation stability; and 2) concrete-related flow properties. The latter is further complicated by reinforcing cage congestion-spacing and the properties of the slurry being displaced during concreting.1

This paper discusses the effects of submerged shaft construction on reinforcing steel bond where ground water or drilling slurry is displaced during concreting.

RESEARCH SIGNIFICANCE

Present specifications applicable to reinforcing bar bond strength from the American Concrete Institute (ACI)2 and the American Association of State Highway and Transportation Officials (AASHTO)3 make no provisions for the effect of tremie placement of concrete in wet conditions; however, some state guidelines4 require reinforcing bar bond verification testing for any excavation stabilizing product (slurry) used during this process. This is done to ensure that previously unapproved products perform to the same level as those currently in practice. This study shows the influence of slurry type on reinforcing bar bond strength.

BACKGROUND

Tremie placement is the requisite method of concreting in submerged conditions whereby a small diameter pipe (for example, 6 to 10 in. [150 to 250 mm]) is used as a concrete delivery conduit to prevent segregation as the concrete flows through the water to the bottom of an excavation. Even within the tremie pipe, means to prevent segregation are used which include: capping/sealing the bottom of the pipe to prevent the intrusion of water as the tremie is lowered to the bottom of the excavation prior to concreting, or use of a separation material such as a foam plug in front of the concrete that is pushed through the tremie or pump line as concrete moves down to the bottom of the excavation. Applications for tremie placement include seal slabs, drilled shafts, cutoff walls, dams, or anytime concrete is placed below water.

During drilled shaft excavation and concreting, sidewall stability is often achieved through hydrostatic pressure wherein a mixture of water and mineral or polymer powder is introduced into the excavation and maintained at an elevation at least 4 ft above the ground water table.4 The effectiveness of this slurry in providing stability is highly reliant on the slurry viscosity, which is tracked using the Marsh funnel test method. This method times how quickly a known volume of a fluid discharges with falling head from a standardized funnel.5 The unit of measure is seconds per quart; the thicker the slurry the higher the Marsh funnel viscosity. Typically, the workable range of these materials is 30 to 50 s/qt for mineral slurry6 and 50 to 90 s/qt for polymer slurry.7 For reference, water has a Marsh funnel value of 26 s/qt, which is the lower limit (1 qt = 0.95 L).

Research focused on tremie-placed seal slabs around steel H-piles and prestressed concrete piles showed that the fluid displaced by the concrete can affect the resulting bond between the pile and seal slab.8-11 Prior to those investigations, the design of seal slabs assumed the bond to be negligible or was fully discounted. Results showed that in some cases, significant bond could be expected. However, when

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the displaced fluid was bentonite slurry, a notable reduction in bond resulted. Figure 1 shows the effect of fluid type on tremie-placed seal slab to steel pile bond. In that study, full-scale seal slabs were cast around W14 x 90 steel pile sections and 14 in. (0.36 m) prestressed concrete piles in caissons flooded with water or bentonite slurry; dry conditions were also prepared as controls. For the steel pile tests, the average water-submerged conditions gave average bond values 4% less than dry, and the bentonite slurry environment resulted in up to a 54% reduction. Similar results were noted for the concrete piles. No polymer slurries were tested.

Based on a study conducted by Butler in 1973, the Federal Highway Administration (FHWA) concludes: “The current state of knowledge on this topic suggests that the use of mineral and polymer slurries for drilled shaft construction does not reduce the bond resistance between concrete and reinforcing bars. There is currently no reason to account for the use of drilling fluids when considering development length of rebar in drilled shafts.” However, that study included only two pullout tests on No. 8 (M25) reinforcing bar where tremie-placed concrete displaced bentonite slurry; one failed in bond splitting failure with 2.25 in. (5.72 cm) of cover in a 30 in. (0.76 m) diameter shaft; the other from the same shaft failed through cover spalling from poor jack alignment. The bentonite slurry was not a pure bentonite slurry but rather a bentonite-polymer blend denoted as high-yield bentonite, a product that has half the suspended solids of pure bentonite and which is often not accepted for bridge construction applications. Although not reported, the Marsh funnel viscosity of the slurry would have been approximately 30 s/qt (1 qt = 0.95 L) based on the documented mixture ratio of 0.21 lb/gal. (25 kg/m³) and mixture ratio to viscosity correlations for this type of slurry. The study also included 12 laboratory-prepared pullout specimens, six with deformed bars and six smooth. Deformed bar tests were further broken out to have three cast-in-dry conditions and three “coated with mud slurry before casting in concrete,” but not tremie-placed, slurry-displaced. In short, the FHWA guidelines are based on five tests, none of which are representative of construction practices.

Deese and Mullins documented concrete build up within the reinforcing cage during tremie placement and where a critical differential concrete height between the center of cage and cover region was required to develop enough pressure to push the concrete radially through the cage and into the cover. The differential height was affected by clear spacing, rate of concrete placement, and the maximum coarse aggregate size. When compared to dry tremie control shafts, the buoyant weight of concrete in slurry-cast shafts was shown to increase the differential height relative to the decrease in buoyant unit weight. These findings were a departure from the previously accepted notions that concrete flow was vertical and uniform across the shaft, easily displaced the slurry (like water under oil), and that upward flow in the cover would scorch the soil side walls of slurry product buildup as well as the reinforcing bar. This also opened the eyes of researchers and owners and revealed that slurry could become trapped around the reinforcing bar and against the side walls.

Numerous studies have shown that use of bentonite slurry to support excavations for drilled shaft results in reduced concrete to soil bond by as much as 50% when compared to polymer or water-cast shafts. Early explanations attributed the reduced side shear to a filter cake that forms as the bentonite suspension/slurry flows into the surrounding soil and deposits the clay particles on the excavation walls. While filter action is somewhat responsible for the presence of the bond-reducing bentonite, trapping of bentonite caused by radial flow was shown to be a far more significant mechanism for the deposition of bentonite along the side walls.

Bowen and later Mobley et al. showed that laitance creases form as radially flowing concrete fills the cover region. The creases radially project from the cage configuration to the surface of the shaft sides. The Deep Foundation Institute (DFI) termed this phenomenon as mattressing, giving the appearance of a quilted mattress cover. The cover integrity, concrete strength, and corrosion protection were all shown to be substantially affected in bentonite cast shafts. Coring the intersection of these creases revealed the concrete was not contiguous, and for high-viscosity bentonite slurry, the cores separated into four pieces defined by the laitance crease locations. Figure 2 shows, from top left to bottom right: a) the buildup of concrete inside the cage noted by Deese and Mullins; b) laitance creases showing the cage projection to the sides of the shaft; c) radial coring the intersection of creases; d) laitance crease inside cored hole walls extending to cage depth; e) core extracted from water-cast shaft with no change in quality; f) core from 60 s/qt (1 qt = 0.95 L) polymer cast shaft with minor void on cover side of main bar; g) core from 40 s/qt (1 qt = 0.95 L) bentonite-cast shaft with void behind main bar and laitance crease extending to the shaft side wall at top of picture; and h) and i) four pieces from the four quadrants of the cores extracted from 50 and 90 s/qt (1 qt = 0.95 L) bentonite-cast shafts, respectively. The four pieces of the cores (all 4 in. [102 mm] diameter) were still coated along the crease interfaces with trapped bentonite despite the wet coring method used. Figures 2(e) through (g) are aligned with the shaft-side walls at the top of the image.

As use of bentonite slurry has been shown to affect all aspects of cast-in-place foundation performance including concrete-to-soil bond, corrosion resistance, seal slab-to-pile
bond, concrete cover strength, and integrity, it is reasonable to assume that the reinforcing bar-to-concrete bond can be similarly affected. Although the FHWA states no effects result from slurry-placed concrete on reinforcing bar bond, the Florida Department of Transportation (FDOT) requires all new slurry products to “demonstrate the bond between the bar reinforcement and the concrete is not materially affected by exposure to the slurry under typical construction conditions, over the typical range of slurry viscosities to be used.” The motivation for this study stemmed from verification tests required to satisfy this specification. Thereby, the effects of various polymer and mineral slurry products were tested over a wide range of viscosities.

**DEVELOPMENT LENGTH AND BOND STRENGTH**

Whereas development length is a practical parameter required to ensure proper reinforcing steel performance, its determination stems from studies\textsuperscript{23-27} focused on the bond stress ($u$) between concrete and reinforcing bars. ACI Committee 408\textsuperscript{28} discussed how resistance factors could or should be computed and applied to development length equations. The report used a database of splice and pullout test results to compute the mean bias (measured/predicted), standard deviation, and the coefficient of variation (COV) values for that data.\textsuperscript{28} The committee report defined the reinforcing bar bond strength reduction or resistance factor ($\Omega_r$) and the effective strength reduction factor ($\Omega_d = \Omega_r / \Omega$) for use in calculating an appropriate development or splice.

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*Fig. 2—Tremie-placed shaft specimens cored to show effects of radial concrete flow.*
length. The effective strength reduction factor simply removes the effect of any resistance factor associated with a given loading type (for example, $\varnothing$ for bending or tension) from the bond resistance factor. Hence, during the computation of a given system resistance/strength (such as bending), the reduction associated with $\varnothing$ is fully in place without compounding the overlapping effects of two different resistance factors. Equations (1) through (4) show how a resistance factor is introduced into development length and bond force equations from ACI 318$^{2}$ and ACI 408R-03 (recommended). While it is not explicitly stated whether or not Eq. (1), ACI 318 development length equation, presently includes this resistance factor, it is assumed based on the ACI 408R-03 report$^{28}$ that one has not been included and that perhaps such a resistance factor should be considered

$$l_d = \frac{3}{40} \frac{f_y}{\lambda} \sqrt{f_c} \left( \frac{\psi_f \psi_y \psi_s}{c_s + K_w} \right) d_b$$

$$T_b = 10.472 \varnothing_b \sqrt{f_c} \left( c_s + \frac{40 A_e}{76.3} \right) l_d$$

$$l_d = \frac{f_y}{(f_c)^{1/2}} \varnothing_d 2400 \omega \alpha \beta \lambda$$

$$T_b = (f_y)^{1/4} \left[ \varnothing_s 59.9 l_d (c_m + 0.5 d_b) + \varnothing_s 2400 A_y \right]$$

$$\{ 0.1 \frac{c_m}{c_m} + 0.9 \} + \left[ 30.88 f_{y_d} \frac{N_A}{n} + 3 \right] f_c^{3/2}$$

Given the noted effect of slurry of various kinds on bond, this study compared the pullout capacity of 227 reinforcing bar specimens tremie-cast in water, mineral, and polymer slurry to evaluate the actual performance. ACI 318 and recommended 408R-03 equations for both pullout capacity (Eq. (2) and (4)) and development length (Eq. (1) and (3)) are used as comparative baselines for reinforcing bar pullout capacities when cast in slurry.

**APPROACH**

The ACI 408R-03 report$^{28}$ defines four different pullout testing configurations, also shown in Fig. 3: Case a) the pullout specimen; Case b) the beam end specimen; Case c) the beam anchorage specimen; and Case d) the splice specimen. For the testing performed during this study, a combination of Case a) and b) was adopted: direct pullout of vertically cast specimens with debonded regions (Fig. 3(e)).

All shaft specimens were tremie-placed after the slurry and cage were already in place. The shaft specimens were tailored to meet FDOT minimum diameter and preferred tightest cage spacing criteria. Specimens were 42 in. (1.07 m) diameter, 24 in. (0.61 m) tall, and were formed with a cylindrical steel sheet metal form. Reinforcing bar spacing provided 6 in. (152 mm) clear spacing for both the longitudinal and circumferential steel. Longitudinal reinforcing bar for pullout specimens were slated to be every other main bar and where pullout bars were not permitted to touch the steel stirrups. Outer steel stirrups were placed outside seven of the main bars that were not tested. One-half inch (13 mm) plastic hoops (simulated stirrups) were used to separate the inner and outer rings of main bars (Fig. 4). The inner seven vertical bars/test specimens (No. 8 or M25) were tied inside the plastic hoops but between the outer seven bars. The tested bars were machined down to 7/8 in. (22 mm) diameter on top, threaded, and were debonded in the upper 8 in. (0.2 m) of embedded length with thin walled PVC pipes. The lower 10 in. (0.25 m) was similarly debonded, resulting in a bonded length of 6 in. (152 mm) where nothing touched the bonded region and concrete was unobstructed from directly contacting the bonded test length (Fig. 3(e)). Debonding the upper portion of the bars was designed to reduce the effects of the jacking-induced compressive stress at the surface (as noted by the ACI 408R-03 report$^{28}$) and was verified through numerical modeling to drastically reduce the compression.
stress in the bonded region. Debonding the lower portion allowed the bonded length to be adjusted.

Pullout bars were cast in sodium montmorillonite, informally known as bentonite (API section 10 clay), synthetic partially hydrolyzed poly acrylamide polymer, or water (natural) slurry. The polymer slurries used were from two different manufacturers, where the same amount of pullout bars were tested per manufacturer. This study examines pullout specimens cast over 6 years, from 2012 to 2018, and seven concrete placements.

For pullout testing, an 8 in. (0.2 m) diameter load cell was placed on lead plates on the surface of the concrete followed by a 60 ton (533 kN) capacity hollow-core hydraulic ram. An upper steel plate and double nuts were used to complete the loading assembly. While Fig. 3 Case (a) is not the preferred testing configuration per ACI 408R-03, Case (e) provided compromise creating a realistic casting condition while mitigating the effects of local compression stresses.

Pullout testing was completed using a manually operated hydraulic pump to provide a slowly applied load rate of approximately 100 lb/s (0.4 kN/s). The load cell and a displacement transducer were monitored with a computerized data acquisition system and sampled at 10 Hz to ensure the peak force was captured. The testing was performed after the concrete reached a minimum compressive strength of 4 ksi (28 MPa). All pullout testing was completed on the same day as compressive cylinder strength testing. Out of the 227 pullout tests, 131 were performed in mineral slurry, 56 in polymer, and 40 in water.

**TEST RESULTS**

Using Eq. (2) and (4), the predicted capacity was calculated for all test specimens where the resistance factor was taken as 1.0. This was then compared to the measured value. In general, the mean values of the experimental results for a given concrete strength agreed with the predicted capacities from ACI 318 and ACI 408R-03 (Fig. 5). As most specimens were cast with FDOT Class IV (4 ksi [28 MPa]) shaft concrete mixture, many of the predicted capacity values were similar (vertical banding).

The bias (measured/predicted) values for all pullout samples were computed using both prediction methods and plotted versus the Marsh funnel slurry viscosity (Fig. 6). The mean bias values for each casting condition are also shown as dashed horizontal lines. A general trend is shown of decreasing bias (and pullout capacity) with increasing viscosity, but like Fig. 5, significant variability is still apparent but now for a given viscosity. Higher-viscosity slurry is required for more porous/free-flowing soils, while lower viscosity is suitable for fine-grained, low permeability soils. While lower-viscosity slurry (close to water) performed better in bond, it is not reasonable to restrict the use of higher-viscosity slurry. Therefore, statistical evaluations of slurry effects were performed lumping the data into the basic slurry types (water, bentonite, and polymer). The raw data and details for each pullout test specimen are included in the Appendix. The Appendix is available at www.concrete.org/publications in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

*Shown in Table 1 are the mean bias, standard deviation, and COV values for the slurry types. Table 1 also includes the previously published values for dry conditions, reported by Darwin et al. and the ACI 408 Committee.

Using the mean bias and standard deviation, lognormal probability density curves were prepared for the two prediction methods (Fig. 7). These curves do not include the effect
of a resistance factor (Eq. 2 and 4, $\Theta_b = 1$). The vertical line shown at 1.0 defines the threshold above which the measured capacity is generally acceptable ($\geq 1.0$) or below which is unacceptable ($< 1.0$).

Using the statistical values from ACI 408R-03 for a dead load/live load ratio of 2, the mean measured/predicted load bias, and the associated coefficients of variation for load (Table 2) along with the values from Table 1 for resistance, Monte-Carlo simulations were run for each condition (dry, water, bentonite, and polymer). The simulations were used to predict the probability of failure using one million randomly generated values for both the load and strength. The failure ratios ranged from 1:2 for bentonite to 1:30 for dry conditions (Fig. 7). It should be noted that the failure ratio is not assigned on the basis of the fraction of bias below 1.0, but rather where the random variations in load and strength result in a strength/load ratio below 1.0.

Using the approach outlined by Darwin et al.\textsuperscript{25} to compute resistance factors for reinforcing bar development length (Eq. (5)), resistance factors were computed using the test data (Table 1) bias ($\bar{r}$) and coefficient of variation (COV or $V_r$) values for both ACI 318 and ACI 408R-03 prediction methods. While not fully expanded in Eq. (5), several variables are taken into consideration when determining the mean value of the random loading variable ($\bar{q}$), and the COV of the loading random variable ($V_{q_0}$) which include: actual-to-nominal dead and live load random variables, dead and live load factors, nominal ratio of live load to dead load, and coefficients of variation pertaining to dead and live loads (Table 2). These values were again obtained from ACI 408R-03\textsuperscript{28} aside from the COV for dead and live loading which were obtained from Darwin et al.\textsuperscript{25} A reliability index $\beta$, value of 3.5, was used.

### Table 1—Mean bias and COV values for various conditions using ACI 318 and ACI 408R-03

<table>
<thead>
<tr>
<th></th>
<th>Dry (ACI)</th>
<th>Water</th>
<th>Bentonite</th>
<th>Polymer</th>
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<tbody>
<tr>
<td></td>
<td>ACI 318</td>
<td>408R-03</td>
<td>ACI 318</td>
<td>408R-03</td>
</tr>
<tr>
<td>Mean bias ($\bar{r}$)</td>
<td>1.23</td>
<td>1.00</td>
<td>1.21</td>
<td>1.23</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.30</td>
<td>0.12</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>COV ($V_r$)</td>
<td>0.24</td>
<td>0.12</td>
<td>0.25</td>
<td>0.26</td>
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</tbody>
</table>

Fig. 5—Measured strength versus predicted strength for ACI 318 (left); and ACI 408R-03 (right). (Note: 1 kip = 4.45 kN.)

Fig. 6—Bias versus slurry viscosity for ACI 318 (left); and ACI 408R-03 (right). (Note: 1 qt = 0.95 L.)
EVALUATION OF FAILURE RATIOS

Implied by Fig. 7 is that the current development length computations have failure ratios of 1:30 for both Eq. (1) and (3) and through the application of resistance factors (Table 3) an acceptable level of reliability can be obtained (Fig. 8). However, all computations discussed to this point have put no limitations on the \((c_b + K_{tr})/d_b\) expression, which is limited by ACI to values of 2.5 or less “to prevent pullout failures.”\(^2\) The effect of this limit is illustrated using the pullout data from the water-cast specimens which in Fig. 7 and Table 3 were shown to have similar statistical values to that of the ACI reported values for dry conditions. For all ACI 318-predicted capacity values for the water data, the \((c_b + K_{tr})/d_b\) term was capped at 2.5 and the bias and COV values were recomputed to be 3.25 and 0.25, respectively. Monte-Carlo simulations were performed to assess the resulting failure ratios with the 2.5 limit and showed no failures in 1 million trials, meaning that use of this limit (2.5) is more conservative than the target reliability index of 3.5 requires. Simulations were again performed where an additional load multiplier was applied to the existing combined live and dead load multiplier (1.33 for DL/LL ratio of 2) and progressively increased until the failure ratio provided a 3.5 reliability index. Figure 9 shows the effect of the \((c_b + K_{tr})/d_b\) limit on failure ratio for water specimens where the load and resistance are normalized by the unfactored load. The mean load is shown to be approximately 1.0 for both cases (limit and no limit), but only after increasing the load by a 1.65 multiplier does the failure ratio increase from 0:1,000,000 to 1:4545 (1:4149 max) when the 2.5 limit is applied. Hence, the 1.65 value is a measure of the conservatism associated with the 2.5 limit (additional safety factor).

The same evaluation was applied to the bentonite and polymer data sets where the \((c_b + K_{tr})/d_b\) term was capped at 2.5 and the load multiplier required to produce a reliability index of 3.5 was determined (Fig. 10). Where water pullout data required a load magnifier (1.65) to produce the target failure ratio, the bentonite and polymer data showed unacceptable failure ratios of 1:3704 and 1:2040. Applying the same multiplier concept to the simulations, unconservative multiplier values of 0.99 and 0.93 would be required to bring the failure ratios down to the target reliability for bentonite and polymer, respectively. Therefore, some consideration for slurry casting conditions is needed and the multiplier

\[
\varphi_b = \frac{p}{\bar{q}} \left(\frac{\bar{q}^2 + \sigma_{\bar{q}}^2}{\bar{q}^2 + \sigma_{\bar{q}}^2}ight)^{\beta}
\]

(5)

Table 3 shows the computed resistance values \(\varphi_b\) for the different slurry types along with the values reported for dry conditions from ACI 408R-03.\(^2\)

<table>
<thead>
<tr>
<th>Parameter Used in Eq. (5)</th>
<th>Value</th>
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</tr>
<tr>
<td>Load factor, LL</td>
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<tr>
<td>DL/LL ratio</td>
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<td>Reliability index</td>
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<tr>
<td>Load bias, LL</td>
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<td>Load COV, DL</td>
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<tr>
<td>Load COV, LL</td>
<td>0.25</td>
</tr>
<tr>
<td>(\bar{q})</td>
<td>0.76</td>
</tr>
<tr>
<td>(V_{\bar{q}})</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Notes: DL is dead load; LL is live load.

Fig. 7—Lognormal probability density for ACI 318 (left); and ACI 408R-03 (right).

Fig. 8—Lognormal probability density for ACI 318 (left); and ACI 408R-03 (right) after applying resistance factors.

Fig. 9—Effect of \((c_b + K_{tr})/d_b\) term on water failure ratios; no limit (left); with 2.5 limit before (red) and after (black) 1.65 load multiplier (right).
values are the same as resistance factors. To produce the same level of conservatism presently in place for dry cast specimens (based on the water cast specimen data), development length factors ($\Psi_{slurry}$) from Monte-Carlo simulations were determined by the ratio of load multipliers to be 1.7 (1.65/0.99) and 1.8 (1.65/0.93) for bentonite and polymer casting environments, respectively.

**DISCUSSION**

Bar cleanliness and epoxy coatings are recognized to affect reinforcing bar pullout capacity. Unclean conditions are to be avoided and epoxy coatings are given a development length factor ($\Psi_v$) of 1.2 or 1.5 depending on cage spacing and cover dimensions. The combination of slurry coating and radial concrete flow around the reinforcing bar cage into the cover region (which is common to tremie placement) presents conditions that also affect reinforcing bar bond. Accommodations for the associated reductions in resistance and variability can be provided through resistance factors or $l_d$ equation cutoff limits for the $(c_b + K_{tr})/d_b$ term. Using either approach, the same level of reliability can be provided to slurry casting conditions by increasing the development length using ratio of load multipliers used for Fig. 9 and 10 or the ratio of resistance factors from Table 3. The ratio of resistance factors stems from using the Table 3 resistance factors in Eq. (1) where an alternate method of determining a development length factor can be established for slurry, $\Psi_{slurry} = l_{d,slurry}/l_{d, dry}$, which simplifies to $\Theta_{dry}/\Theta_{slurry}$. For water, bentonite and polymer casting conditions, the resistance factor ratios from Table 3 values give development length factors of 1.05, 1.76, and 1.86, respectively. Using the ratio of the simplistic load multipliers in Fig. 9 and 10 to satisfy

$$\beta = 3.5$$

in the Monte-Carlo simulations, the multipliers were similar, where bentonite and polymer conditions require development lengths 1.7 and 1.8 times longer than water development lengths, again respectively, to provide the same level of reliability. Water conditions were shown to be conservatively satisfactory when the $(c_b + K_{tr})/d_b$ limit of 2.5 was imposed.

Both ACI and AASHTO provide tables that further simplify the development equations dependent on concrete strength, bar size, bar spacing or cover dimensions, and transverse reinforcement. Two categories are established that set the value of the term $(c_b + K_{tr})/d_b$ in Eq. (1) to 1.5 or 1. Case 1 refers to preferred main bar clear spacing, clear cover, and stirrup spacing criteria $(c_b + K_{tr})/d_b = 1.5$; Case 2 refers to all other conditions $(c_b + K_{tr})/d_b = 1.31$. This further reduces the probability of failure, but using the same logic previously presented, slurry-cast reinforcing bar would inherently be less reliable while still perhaps acceptable.

To date, the authors are unaware of any reinforcing bar bond/development length-related failures in drilled shafts, which could make the argument there is no need to consider the findings of this study. This could be due to the conservatism built-in to development length equation via limits, or reinforcing bar splices in drilled shafts are not likely to be in high moment regions (for example, directly under the footing in overwater bridges). In such cases, development can be adequately provided via a hook in the dry cast footing above or sufficiently long lengths within the shaft length below. Further, staggered splice locations are often employed to reduce cage congestion and promote concrete flow into the cover region; per AASHTO, “no more than 50 percent of the reinforcement shall be terminated at any section.” Nevertheless, splices are designed to develop the bar without regard for the actual local moment demands and if the same level of reliability is sought for slurry-cast reinforcing bar, development lengths should be increased accordingly. No adjustment is necessary for water casting conditions.

The unexpectedly higher values for polymer ($\Psi_{slurry}$) were attributed to the high COV for polymer data which may have stemmed from testing various manufacturer products. This suggests that further delineation of polymer slurry prod-
ucts by exact chemical composition may be warranted, but at present, field construction practices make no distinction. Bentonite falls under strict API guidelines for uniformity.5

When reviewing possible future use of the ACI 408R-03 development length computations, Eq. (3), the same development length ratio/slurry factor determination should be considered, but the simple resistance factor ratio is not valid due to the formulation of that equation. The computed development length multiplier \((l_{d,slurry}/l_{d, dry})\) for water conditions showed a uniform multiplier \((\Psi_{slurry})\) value of 1.3, applicable for all concrete strengths. Bentonite and polymer slurry conditions showed a subtle change through the range of concrete strengths where the multiplier ranged from 1.8 to 1.9 and 2.6 to 2.8, respectively (Table 4).

Finally, when applying the same procedure for resistance factor determination to AASHTO load factors, mean bias of predicted loads, the corresponding coefficients of variation for AASHTO type loads,30 and the same dead load to live load ratio (2.0) used in this study (Table 5), the computed resistance factors using Eq. (5) were strikingly similar to those determined for the ACI 318 in Table 3. As a result, the same development length multipliers computed for ACI 318 prediction methods should be considered for AASHTO applications as well. Details of this analysis can be found elsewhere.29

**CONCLUSIONS**

Present ACI, FHWA, and AASHTO specifications make no adjustments to reinforcing bar development or lap splice lengths for tremie-placed, slurry-displaced concreting conditions. However, considerations for bar cleanliness (oil or mud) and epoxy coatings are well documented. This study presented the reinforcing bar pullout test results from 227 specimens tremie-cast in commonly used mineral, polymer, or natural (water) drilling slurry. While the average pullout resistances were in line with present prediction methods, the statistical variations in resistance when coupled with published variations in load showed possible failure ratios of 1:2 and 1:3.5 for bentonite and polymer casting environments, respectively. Specimens cast in a water environment showed similar failure ratios as dry conditions which were on the order of 10 to 15 times better than slurry at 1:22 and 1:30, respectively.

Limiting the value of the \((c_b + K_b)/d_b\) term to 2.5 in the development length equation (Eq. 1) increases reliability of reinforcing bar bond in slurry casting environments where the failure ratios fall to 1:3704 for bentonite and 1:2040 for polymer slurry conditions. Both fail to meet the target reliability index of 3.5 without a development length factor for slurry \((\Psi_{slurry})\). For each casting environment, resistance factors were computed using a reliability index of 3.5 and Monte-Carlo simulations showed reinforcing bar pullout failure ratios to be acceptably low. These resistance factors when applied to ACI 318 or AASHTO development equations suggest that present development length values should be increased by 1.9 for polymer or 1.8 for bentonite slurry environments (essentially doubled) to achieve the same reliability as dry conditions. When considering the coating factor for epoxy is as high as 1.5, these values are reasonable. For water casting environments, only subtle variations were noted from dry conditions, which were deemed inconsequential.

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**NOTATION**

\[ A_b = \] area of bar being developed or spliced
\[ A_{tr} = \] area of transverse reinforcement crossing potential plane of splitting adjacent to reinforcement being developed
\[ c_b = \] least of side cover, concrete cover to bar or wire, or one-half center-to-center spacing of bars or wires
\[ c_{bot} = \] bottom concrete cover for reinforcing bar being developed
\[ c_d = \] maximum of \(c_{bot}\) or \(c_{tr}(c_d/c_m \leq 3.5)\), in.

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**Table 5—AASHTO parameters and slurry factors**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Load factor, DL</td>
<td>1.25</td>
</tr>
<tr>
<td>Load factor, LL</td>
<td>1.75</td>
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<tr>
<td>DL/LL ratio</td>
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<tr>
<td>Reliability index</td>
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<tr>
<td>Load bias, DL</td>
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<tr>
<td>Load bias, LL</td>
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<tr>
<td>Load COV, DL</td>
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<tr>
<td>Load COV, LL</td>
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<td>(\Omega_{dry})</td>
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<tr>
<td>(\Omega_{water})</td>
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<tr>
<td>(\Omega_{bentonite})</td>
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<tr>
<td>(\Omega_{polymer})</td>
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<td>(\Psi_{water})</td>
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<tr>
<td>(\Psi_{bentonite})</td>
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</tr>
<tr>
<td>(\Psi_{polymer})</td>
<td>1.9</td>
</tr>
</tbody>
</table>
References


2. ACI Committee 318, “Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary (ACI 318R-14),” American Concrete Institute, Farmington Hills, MI, 2014, 519 pp.


