Minimum Confinement Reinforcement for Prestressed Concrete Piles and a Rational Seismic Design Framework

The following comments relate to "Minimum Confinement Reinforcement for Prestressed Concrete Piles and a Rational Seismic Design Framework,"[1] by S. Sritharan, A.-M. Cox, J. Huang, M. Suleiman, and K. Arulmoli, which appeared in the January–February 2016 issue of *PCI Journal*.

This is an interesting and useful paper, but it has missed or omitted an important reference. The American Concrete Institute's (ACI's) *Guide to Design, Manufacture, and Installation of Concrete Piles*, ACI 543-12,[2] has an extensive discussion of spirals. It also includes a discussion and description, with multiple references, of damage to piles in various seismic events. The paper by Sritharan et al. seems to lament the lack of this damage information.

A few other comments may be helpful. Equation (1), reproduced from the *PCI Design Handbook: Precast and Prestressed Concrete* [3] is in the format of an earlier New Zealand code (NZS) equation, with some of the constants changed.

$$\rho_s = 0.25\left(\frac{f_c^{'}}{f_{yh}}\right)\left(\frac{A_g}{A_{ch}}-1\right)\left(0.5+\frac{1.4P}{f_c^{'}A_g}\right) \text{ but not less than } 0.12\left(\frac{f_c^{'}}{f_{yh}}\right)\left(0.5+\frac{1.4P}{f_c^{'}A_g}\right) \quad (1)$$

where

ρ_s = volumetric ratio of spiral confinement reinforcement

$f_c^{'}$ = compressive strength of unconfined concrete

f_{yh} = yield strength of transverse reinforcement

A_g = gross section area of the concrete pile section

A_{ch} = cross-sectional area of confined core concrete section, measured out-to-out of the spiral reinforcement as defined by ACI 318-05

P = design axial force (derived from overstrength consideration)

The definitions of terms of the current New Zealand equation, Eq. (5) in this paper, contain an error.

$$\rho_s = \frac{(1.3-p_l m)}{2.4}\left(\frac{A_g}{A_{ch}}\right)\left(\frac{f_c^{'}}{f_{yh}}\right)\left(\frac{P}{\phi f_c^{'}A_g}\right)-0.0084 \text{ but not less than } \left(\frac{A_{st}}{110D^{'}}\right)\left(\frac{f_y}{f_{yh}}\right)\left(\frac{1}{d_b}\right) \quad (5)$$

where

m = nondimensional ratio = $\dfrac{f_y}{0.85f_c^{'}}$

ϕ = curvature

A_{st} = total area of mild longitudinal steel reinforcement

$D^{'}$ = core concrete diameter measured to the center of the transverse reinforcement

f_y = yield strength of longitudinal reinforcement

d_b = diameter of the reinforcing bar

The variable ϕ is defined as *curvature* under the equation, but ϕ without a subscript is defined as *internal friction angle* in the Notation section at the end of the paper. All curvatures ϕ defined in Notation have subscripts. The placement of ϕ in the equation suggests that it is a strength reduction factor. In NZS 3101 part 1[4] Eq. (10-40), a related equation for the area of transverse reinforcement in rectangular form, uses ϕ as a strength reduction factor.

$$A_{sh} = \left[\frac{(1.3 - p_t m) s_h h^{"}}{3.3}\right]\left(\frac{A_g}{A_c}\right)\left(\frac{f_c^{'}}{f_{yt}}\right)\left(\frac{N_o^*}{\phi f_c^{'} A_g}\right) - 0.006 s_h h^{"} \qquad \text{NZS Eq. (10-40)}$$

where

A_{sh} = total effective area of hoop bars and supplementary cross-ties in the direction under consideration within spacing s_h

p_t = ratio of nonprestressed longitudinal column reinforcement = A_{st}/A_g

s_h = center-to-center spacing of hoop sets

$h^{"}$ = dimension of concrete core of rectangular section, measured perpendicular to the direction of the hoop bars, measured to the outside of the peripheral hoop

A_g = gross area of section

A_c = area of concrete core of section measured to outside of peripheral spiral or hoop

$f_c^{'}$ = specified compressive strength of concrete

f_{yt} = lower characteristic yield strength of spiral, hoop, stirrup-tie, or supplementary cross-tie reinforcement

N_o^* = design axial load derived from overstrength considerations (capacity design)

ϕ = strength reduction factor

Equation (10-38), which is cited as Eq. (5) in this paper, lacks the ϕ term in the version available to me, but this is probably a misprint. The symbol ϕ is clearly a strength reduction factor in NZS 3101.

$$\rho_s = \left[\frac{(1.3 - p_t m) s_h h^{"}}{2.4}\right]\left(\frac{A_g}{A_c}\right)\left(\frac{f_c^{'}}{f_{yt}}\right)\left(\frac{N_o^*}{\phi f_c^{'} A_g}\right) - 0.0084 \qquad \text{NZS Eq. (10-38)}$$

where

ρ_s = ratio of volume of spiral or circular hoop reinforcement to total volume of concrete core

The second part of Eq. (5) is correctly identified as a "not less than" case, but that is an incomplete description. In NZS 3101[3] this is Eq. (10-39), which also says, "for lateral restraint of longitudinal bars against premature buckling."

$$\rho_s = \left(\frac{A_{st}}{110 d^{"}}\right)\left(\frac{f_y}{f_{yt}}\right)\left(\frac{1}{d_b}\right) \qquad \text{NZS Eq. (10-39)}$$

where

$d^{"}$ = depth of concrete core of column measured from center-to-center of peripheral rectangular hoop, circular hoop, or spiral

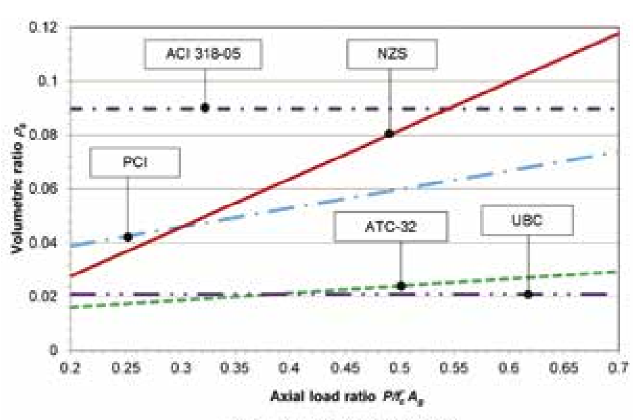

FIGURE 1

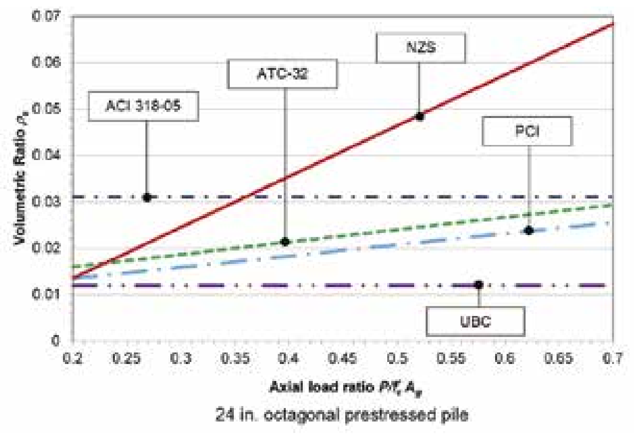

FIGURE 2.

Premature buckling is, of course, not an issue for a pile containing only prestressed strands because the strands will have a significant tension stress when the surrounding concrete fails.

The *Uniform Building Code* requirements[5] shown in the paper must have a misprint because it says that the minimum spiral steel ratio is 0.021 for all sizes. **Figure 2** shows 0.021 for the 14 in. (360 mm) square pile and a smaller value, perhaps 0.012, for the 24 in. (610 mm) octagonal pile.

A simple moment-curvature relationship for a pretensioned pile can be approximated by two straight lines. The first line is from the origin to the point of initial cracking, and second line is from the cracking point to ultimate, considering ultimate to be the point of initial concrete crushing. This is a reasonable, but conservative, approximation because there is typically a great reduction in flexural stiffness accompanying first cracking. Better moment-curvature relationships can be constructed at the expense of considerable arithmetic.

William Gamble
Professor emeritus, University of Illinois at Urbana-Champaign
Urbana, Ill.

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Authors' response

The authors greatly appreciate the reviewer's interest in "Minimum Confinement Reinforcement for Prestressed Concrete Piles and a Rational Seismic Design Framework,"[1] and his useful discussion.

The reviewer's first point was about the lack of reference to ACI 543-12,[2] which was published by ACI Committee 543. When the study was undertaken by the authors, an earlier version of the reference that was published in 2000[3] was included in the literature review. This particular reference was not cited because it adopted the confinement equations published in the *PCI Design*

Handbook: Precast/Prestressed Concrete[4] for piles with circular confinement in high seismic regions. By incorporating the *PCI Design Handbook* in the study, the suggested confinement expression was examined and reported in the paper. ACI 543-12 also cites the *PCI Design Handbook* for circular confinement in piles and discusses the NEHRP 2003[5] and IBC 2006[6] provisions.

Within its scope, the published study examined the literature summarizing the response of piles in the field in order to establish an upper-bound value for seismic curvature demand on piles. However, this effort intentionally excluded pile response or damage that was influenced by soil liquefaction and lateral spread because soil conditions and soil-pile interaction—thus curvature demand on piles—in these cases are different. The study summarized in the paper focused on piles embedded in soils defined according to ASCE 7-10[7] soil classification A through E and assumed no failure of soil. Soil vulnerable to failure falls in soil class F. Although ACI 543-12[2] identifies several examples, the majority of the cited pile damage occurred in poor soil conditions and the curvature demand on piles in most cases was not back calculated, which was what we reported to be scarce in the literature.

For example, a reference cited in ACI 543-12[2] is a 2001 study completed by Bobet et al.[8] that includes a summary of pile response in 59 cases, 37 of which were affected by liquefaction and/or lateral spreading of soil. For several other cases, the pile experienced no damage; insignificant damage; or an undesirable failure mode, such as shear failure or pile pullout. There is only one case[10] for which the curvature demand on the pile was estimated, and this information was already included in the study by the authors.[1]

It is the opinion of the authors that if the soil has the potential to fail, an approach is to use a suitable ground-improvement technique to enhance the soil behavior[9] and design the pile using the improved soil parameters. Alternatively, the pile design could accommodate the loading from the weak soil (for example, laterally spreading ground). The latter case would increase the pile flexibility. Therefore, if a pile displacement suggested in the paper is targeted, the corresponding pile could be designed with a curvature ductility capacity below 18.

Gamble suggests that the moment-curvature relationship for a pretensioned pile can be approximated by two straight lines with the first line going from the origin to the initial cracking and the second line connecting the cracking point to the ultimate condition, with the ultimate being defined at initial concrete crushing. Although it is relatively simple, this approach and several other options considered in the study have consequences and are considered unsatisfactory. More accurate idealization of the moment-curvature relationship simplifies the confinement equation and its reliability in ensuring the target curvature capacity for the pile section designed with the suggested equation. Therefore, using the idealization suggested in the paper is important to ensure that the targeted curvature capacity can be achieved when using the proposed confinement equation.

The following corrections to the paper are suggested based on the feedback provided by Gamble on other issues:

- The variable ϕ in Eq. (5) of the manuscript defines the strength reduction factor; a value of 1.0 was used when finding the confinement reinforcement quantities for comparison with those obtained from other recommended equations.[1]
- For a detailed description of Eq. (5), the reader is referred to NZS 3101.[11,12]
- The UBC requirements should read as follows: $\rho_s \geq 0.021$ for piles 14 in. (360 mm) and smaller; and $\rho_s \geq 0.012$ for piles 24 in. (610 mm) and larger.[13]

Sri Sritharan
Grace Miller Wilson and T. A. Wilson Engineering Professor; Department of Civil, Construction, and Environmental Engineering; Iowa State University
Ames, Iowa

Ann-Marie Cox
Structural engineer, Raker Rhodes Engineering
Des Moines, Iowa

Jinwei Huang
Structural engineer, Shanghai Xuhui Land Development Co.
Shanghai, China

Muhannad Suleiman
Assistant professor of geotechnical engineering, Lehigh University
Bethlehem, Pa.

K. Arulmoli
Principal of Earth Mechanics Inc.
Fountain Valley, Calif.

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Comments?