CONFINEMENT OF PRESTRESSED CONCRETE BRIDGE PILING FOR SEISMIC LOADS

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ABSTRACT

Curvature (rotational) ductility of prestressed piles is extremely important during a seismic event. The best way to ensure ductility is to provide adequate confinement using a continuous spiral along the pile length.

Many of today's design specifications can trace the origin of their requirements concerning confining reinforcement to ACI 318-02 Equation 10-6, which was first incorporated into the code in 1963. The resulting spiral is often referred to as an "ACI Spiral". It has been widely adopted for column design under typical service state loads, but its adoption for prestressed piling in seismic risk areas is less universal.

For concentrically loaded compression members, the ACI Spiral enhances the concrete core capacity after the cover spalls off. In a pile, however, the axial capacity is normally controlled by the capacity of the surrounding soils. Thus, piles are often loaded well below their axial capacity, and flexural ductility becomes more important than maintaining the full axial load-carrying capacity of the core.

Research has shown that for low levels of axial load, adequate ductility in a seismic event can be achieved with lighter spirals than that required by the ACI Code. This paper is intended to summarize the historical progression of code-mandated spiral quantities, the research upon which it was based, and the results of recent research. Recommendations are made for proposed design considerations.

Keywords: Prestressed, Piles, Seismic, Ductility, Design

INTRODUCTION

Curvature (rotational) ductility of prestressed piles is extremely important during a seismic event. The best way to ensure ductility is to provide adequate confinement reinforcement using a continuous spiral along the pile length.

Code requirements for the quantity of spiral in prestressed concrete piles vary, particularly in regions where plastic hinging may occur as the result of lateral loads. Many of the building and bridge design specifications in use today, including the *AASHTO LRFD Specifications*, can trace the origin of their requirements concerning spiral reinforcement to ACI 318-02 Equation 10-6, which was first incorporated into the code in 1963. The resulting spiral is often referred to as an “ACI Spiral”. It has been widely adopted for column design under typical service state loads, but its adoption for seismic design of prestressed piling is less universal.

For concentrically loaded compression members, the ACI Spiral enhances the concrete core capacity by replacing axial strength lost when the cover spalls off. The spiral also enhances flexural and shear strength, and prevents premature buckling of longitudinal reinforcement. In piles, however, the axial capacity is normally controlled by the capacity of the surrounding soils, not the structural capacity of the pile itself. Thus, in many cases, piles are loaded well below their axial capacity, and flexural ductility becomes more important than maintaining the full axial load-carrying capacity of the core.

Although the ACI Spiral generally ensures ductile behavior in a prestressed pile, it is often difficult to provide the required quantity of steel. The result is a heavy and closely spaced spiral that greatly increases the cost of a pile and makes fabrication difficult. In addition, as the pitch becomes smaller, there is an increased tendency for the concrete cover to spall off during pile driving.

Research has shown that for low levels of axial load, adequate ductility in a seismic event can be achieved with lighter spirals than that necessary to maintain the axial capacity of the pile. This paper is intended to summarize the historical progression of code-mandated spiral quantities and the research behind them. The focus is on confining reinforcement for prestressed piles of "normal" size and shape (to be explained subsequently) in regions of high seismic risk and does not address the requirements for low to moderate seismic zones. A graphical comparison of the spiral quantities required by the various specifications is made.

Recommendations for developing a more rational seismic design criteria for prestressed piles are presented. These recommendations are specific to prestressed concrete piles for bridges and attempt to address all relevant considerations, including:

- Required volume and spacing of confining reinforcement
- Effects of pile size and spiral/tie configuration
- Ductility / rotational capacity requirements

- Plastic zone delineation; requirements inside and outside the plastic zone
- Pier / bent geometry and foundation member redundancy
- Effects of pile head restraint and support conditions

PROBLEM DESCRIPTION

Prestressed concrete piling can be designed to resist the extreme loading conditions from seismic movements without experiencing failure if appropriate design and detailing procedures are followed. Curvature, or rotational, ductility in prestressed piles is extremely important during a seismic event and is a function of many factors. As with other concrete members subjected to bending, it is preferable to have a slightly under-reinforced section, which will allow significant yielding of primary reinforcement prior to crushing of concrete. Ductility in axial-bending members can be increased by providing lateral confinement, reducing the primary reinforcement ratio, reducing the primary reinforcement yield strength, increasing the concrete compressive strength or reducing the axial compression load on the pile.

ROTATIONAL DUCTILITY

The best way to ensure ductility in a flexural compression member is to provide adequate confining reinforcement, such as a continuous spiral, in the compression zone along the member. The size and pitch of spiral required, expressed as the ratio of spiral volume to core volume, ρ_s, varies depending on the magnitude and distribution of bending curvature and potential plastic hinge regions in the pile.

Although the ACI Spiral generally ensures ductile behavior, it can be extremely difficult to provide the resulting amount of spiral reinforcement in a pile. The situation is exacerbated with square piles using longitudinal reinforcement arranged in a circular pattern because the ratio A_g/A_c is unfavorable for square members containing round spirals. The ratio is also particularly unfavorable for small piles and piles using higher strength concrete. The determination of spiral ratio, steel area and spacing for an ACI Spiral is unrelated to flexural or shear requirements. Instead, the equation determines the confinement required to sustain a given axial load after the concrete cover has spalled off. The result is a heavy and closely spaced spiral that greatly increases the cost of a pile and makes fabrication difficult (**Figure 1**.)

The designer should carefully assess the requirements for spirals in piles designed for seismic conditions. The increased material and labor costs and greater difficulty in manufacturing may cause a prestressed concrete pile option to be uncompetitive when compared to other foundation alternatives. Heavy spirals cause problems for precast piles, more so than for cast-in-place columns, because the former are cast in the horizontal position. Large spiral diameters and reduced spiral pitches tend to make concrete placement and consolidation difficult. Concrete must be placed and vibrated through two layers of hoop legs or spiral along the entire length of the pile. Excessively large spiral wire at a close pitch (< 2 in.) can cause congestion within the pile and make it difficult to place low slump concrete with normal size coarse aggregate. Additionally, as the pitch becomes smaller, there is an increased tendency for the concrete cover outside the spiral to spall off during pile driving.

Research has shown that adequate pile ductility in a seismic event can be achieved with lighter spirals than the ACI Spiral **(Sheppard, 1983; Joen, 1990)**. The ACI Spiral equations were derived for axial compressive strength considerations, but the axial strength of a pile is rarely governed by its structural capacity. It is usually controlled by the bearing capacity of the soil. Therefore, the structural capacity of the core alone, without the contribution of the cover, is often sufficient to resist the factored loads on the pile. Under such conditions, the ACI Spiral equation can be safely neglected in the design of piles as long as the confining reinforcement is sufficient to resist the factored shear on the section and to prevent buckling of the longitudinal reinforcing bars and tendons under large lateral deformations. This practice is consistent with the provisions of Section 21.4.4.1 of ACI 318-02 (2002), which state: "If the design strength of member core satisfies the requirement of the design loading combinations including earthquake effect, Eq. (21-3) [rectangular hoop equivalent to Eq. (10-6)] and (10-6) need not be satisfied." This concession applies generally to concrete columns designed for seismic loads but takes on even greater significance for prestressed concrete piles.

HISTORY / DEVELOPMENT OF SPECIFICATIONS

Assuming that one can justify neglecting the ACI Spiral requirements, the question becomes, “What volume of spiral will provide adequate rotational ductility to resist anticipated deformations during a seismic event?” The answer to this question is clouded by the fact that the *AASHTO LRFD Specifications*, and other current specifications, do not explicitly address the structural design of prestressed concrete piles. They rely on general provisions developed for design of reinforced concrete compression members, and more specifically, for columns in buildings.

It should be recognized that a prestressed concrete pile represents a very specialized type of compression member – a slender, prestressed concrete foundation member. The relative importance and performance of an individual pile in a bridge structure is dependent on a number of factors, including:

- The level of axial compression or tension in the pile, including the effect of prestressing
- Lateral support along the member and the degree of confinement provided by this support (with due consideration for soil liquefaction in a seismic event)
- The degree of redundancy afforded by the foundation (i.e., pile bent versus a multi-pile footing)
- Rotational and lateral restraint conditions at the pile head

While some specifications over the years have adopted the ACI Spiral equation without change, others have modified the equation based on piling-related research. The remaining specifications have developed other methods based on research or empirical methods. Besides differing in the volume of spiral required, several of the major specifications differ in how they define the locations and limits of the ductile, or potential plastic hinge, regions of a pile in a seismic event. This paper examines the historical progression of spiral requirements and the research on which they are based.