Engineering Structures 105 (2015) 220–230

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Investigation of ultra high performance concrete piles for integral abutment bridges

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ARTICLE INFO

Article history:
Received 9 October 2014
Revised 5 September 2015
Accepted 8 October 2015

Keywords:
Ultra High Performance Concrete (UHPC)
Pile driving analyzer
Vertical load test
Lateral load test
Pile foundation
Soil-structure interaction

ABSTRACT

The American Association of State Highway Transportation Officials (AASHTO) recently calls for increasing service life of bridges and optimizing structural systems. To extend its service life, this paper focuses on using an advanced Ultra High Performance Concrete (UHPC) as an alternative material for integral abutment bridge pile foundations. A parametric analysis was performed to understand the effects of key parameters in the performance of the UHPC piles. Results from this study provided the necessary technical background for selecting a test site and designing a field test for the UHPC pile as well as for future field monitoring of UHPC pile. A series of field testing was conducted to evaluate the behaviors of two 230-mm, H-shaped, UHPC test piles (i.e., P3 and P4), driven in clayey silt to silty clay, as well as a structural splice on P4 during pile installation, vertical, and lateral load tests. The field test results confirm that UHPC piles have exceeded the target axial and lateral capacities, sufficient driving resistance, and adequate performance of the splice. The analytical and experimental results provided the technical background knowledge of using UHPC and established the basis for more future research that would consider other influential factors.

1. Introduction

The depletion of natural resources, continuous deterioration of infrastructure, and increasing maintenance costs propose great challenges to the American Association of State Highway Transportation Officials (AASHTO) and many state Departments of Transportation (DOT). According to the report on grand challenges issued by the AASHTO Highway subcommittee on bridge and structures in 2005 [1], a quarter of our nation's 590,000 bridges, including their substructures and foundations, were classified as structural deficient or functionally obsolete, primarily due to material deterioration. Research areas on substructures and foundations focusing on correction protection, strengthening of piers and extending service life are encouraged. According to Lampo et al. [2] the US spent more than $1 billion annually on maintenance and replacement of conventional pile foundations that were degraded from chloride attack on concrete, steel corrosion and marine borer attack on timber.

To address these challenges the AASHTO [1], in the beginning of 2005, called for more research advancements focusing on extending service life of bridges to 75 years with minimal maintenance and optimizing structural systems using new materials. To overcome these challenges, innovative methods, such as the use of an advanced Ultra High Performance Concrete (UHPC) material that has been applied to bridge superstructures [3–7], are being investigated to extend the service life of a bridge. Since the UHPC has better durability properties than those of a conventional concrete, as measured by permeability tests, freeze–thaw tests, scaling tests, abrasion tests, resistance to alkali-silica reactivity, and carbonation, structures use UHPC are expected to have a longer service life and require less maintenance [8]. Many existing and older bridges were supported by pile foundation systems made of timber, steel and concrete. Each pile type has its advantages and limitations. Timber piles are susceptible to damage and decay when they are installed above the water table and are subjecting to alternate wetting and drying cycle while its durability is a function of site-specific conditions. Timber pile splices are difficult to install and generally avoided. However, timber piles are recommended for the construction of bridge fender systems due to the good energy absorption properties of wood [12]. Although steel piles are commonly used in the US [9], they are vulnerable to corrosion

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http://dx.doi.org/10.1016/j.engstruct.2015.10.009
0141-0296/

[10], local bucking under harsh driving conditions [11], as well as the tendency to deviate from the designed location when obstructions are encountered [12]. However, steel H-piles can easily be extended or reduced in length, has strong splices to resist compression and bending, and are effective when driven into soft rock or dense materials [12]. Precast/prestressed concrete piles have relatively high breakage rate, especially when they are to be spliced [12]. Furthermore, they are susceptible to cracking as a result of large compressive and tensile stresses developed during driving [13]. However, concrete piles are usually resistant to corrosion and exhibit high load capacity [12]. When the limitations of these conventional pile foundations are facilitated by the site-specific condition and the average age of these foundations approach their service life, maintaining and replacing bridge substructures becomes a challenging task.

To minimize drivability challenges, extend a target service life, and possibly reduce maintenance costs, piles made of UHPC material can be considered as an alternative to the conventional piles. The foundation system can be optimized by utilizing the advantages of UHPC, such as (1) excellent durability characteristics as a result of small capillary porosity; and (2) very high compressive (180–207 MPa) and tensile (12 MPa) strengths [14]. Recognizing the benefits of UHPC, the first UHPC pile research project (Phase I) was conducted in the State of Iowa, USA to understand the behavior of two 10.7 m-long UHPC piles (i.e., UHPC-1 and UHPC-2), driven in loess on top of a hard glacial till clay soil and subjected to both vertical and lateral load tests [15]. The UHPC piles were designed with dimensions and weight similar to that of a referenced steel HP 250 × 85 pile (see Fig. 1). The UHPC pile section was reinforced with ten 13-mm diameter prestressing strands with no shear reinforcement. The concrete cover was reduced from 32 to 19 mm due to the high strength and durability of UHPC. The promising findings of this research summarized below provided the necessary background to advance the knowledge of UHPC piles discussed in this paper.

- The UHPC piles, with an H-shape section and the top 230-mm casted as a solid 254-mm by 254-mm block, has been successfully driven with no visible cracking using the same Delmag D19-42 hammer used to drive steel H-piles without a pile cushion.
- The average axial load capacity of the UHPC-1 was about 86% greater than that of the steel H-pile as verified using static analysis methods, dynamic analysis methods, and a static load test.
- The increase in axial pile capacity due to pile setup was observed.
- The performance of UHPC closely matched with the estimation using the LPILE software [17].

Recognizing the benefits of UHPC piles and the positive outcomes of Phase I research, additional research on the UHPC pile (Phase II that is discussed in this paper) was untaken to further characterize the behavior, verify the performance of UHPC piles, and facilitate the implementation of UHPC pile foundations in future bridges. Among the many objectives of the Phase II research project, this paper focuses on (1) analysis of UHPC piles in integral abutments: moment curvature and parametric analyses; (2) the production of two UHPC piles and a newly designed pile splice; (3) driveability analysis of UHPC piles with a full H-shape section; (4) the performance of the pile splice connection under a lateral load test; (5) the behavior of UHPC piles bending about both strong and weak-axes; and (6) testing the UHPC piles to failure in field.

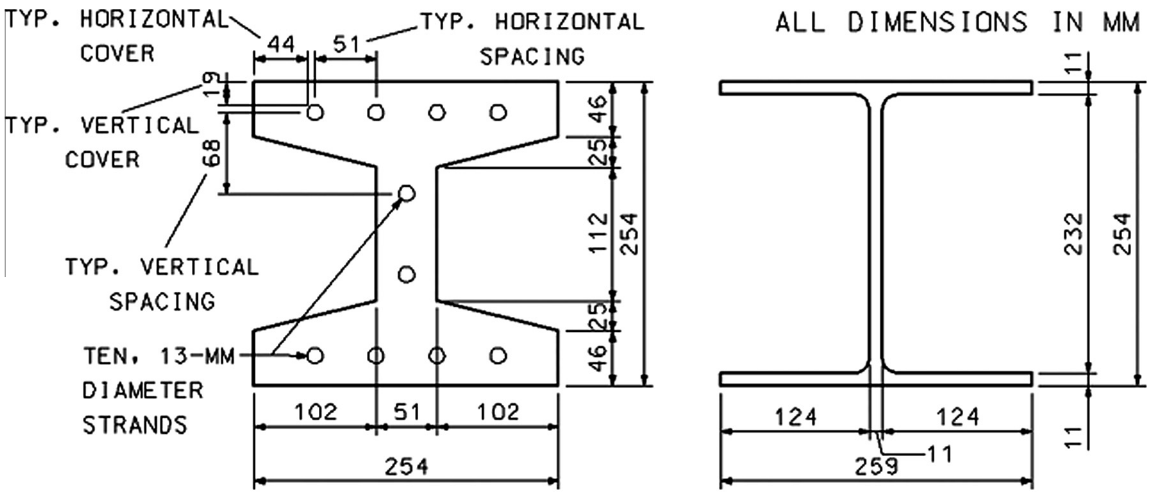
2. Analysis of UHPC piles in integral abutments

2.1. Moment curvature analysis

The moment–curvature responses under different axial loads are required as an input in a lateral load analysis. The moment–curvature response program for UHPC piles developed by Vande Voort [14] and modified by Garder [16] is based on the following assumptions:

- Plane sections remain plane;
- Prestress losses occur due only to elastic shortening and shrinkage of UHPC;
- Strands have perfectly bonded to UHPC outside of the transfer regions;
- Effective prestressing is applied at the centroid of the section;
- Bending only occurs about the weak flexural axis;
- Initial prestressing does not induce any inelastic strains on the strands; and
- Axial loads applied through the centroidal axis of the pile.

The moment–curvature program divides the cross-section into 100 small segments and calculates the stresses and strains for each segment at a given curvature. The stress and strains are then con-



(a) H-shape UHPC pile section (b) Steel HP 250×85 pile section

Fig. 1. Cross-sectional details of a UHPC pile compared with a steel HP 250 × 85 pile (adopted from Suleiman et al. [15]).