Design and Performance Verification of a Bridge Column/Footing/Pile System for Accelerated Bridge Construction (ABC)

tech transfer summary

March 2020

RESEARCH PROJECT TITLE
Design and Performance Verification of a Bridge Column/Footing/Pile System for Accelerated Bridge Construction (ABC)

SPONSORS
Iowa Highway Research Board
(IHRB Project TR-673)
Iowa Department of Transportation
(InTrans Project 14-495)

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The Bridge Engineering Center (BEC) is part of the Institute for Transportation (InTrans) at Iowa State University. The mission of the BEC is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges.

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This project successfully developed and verified through laboratory and field tests the performance of a bridge substructure system that utilizes precast columns, precast footings, and steel H-piles.

Problem Statement

A full substructure system involving prefabricated bridge columns, footings (or pile caps), and piles has not been used in practice because of the lack of suitable connections and performance validation of such a system.

Objectives

- Develop a bridge column/footing/pile system that can be implemented economically and effectively using accelerated bridge construction (ABC) methodologies
- Validate the performance of the proposed connection details through laboratory tests
- Validate system performance through an outdoor test with consideration of soil-foundation-structure interaction
- Formulate design recommendations and details based on test results

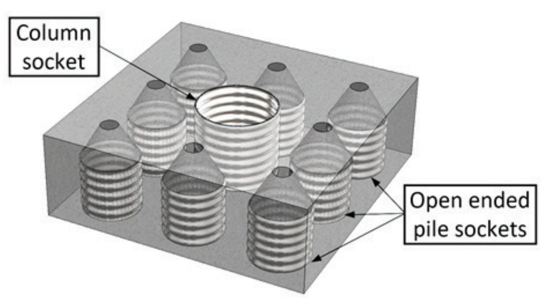
Background

About one in five bridges in Iowa were designated as structurally deficient in 2019 and require significant maintenance, rehabilitation, or replacement. ABC using prefabricated bridge components helps to improve the condition of bridges as it allows for faster and better repairs or bridge replacements. The Iowa Department of Transportation (DOT) has successfully implemented prefabricated components in bridge superstructure construction.

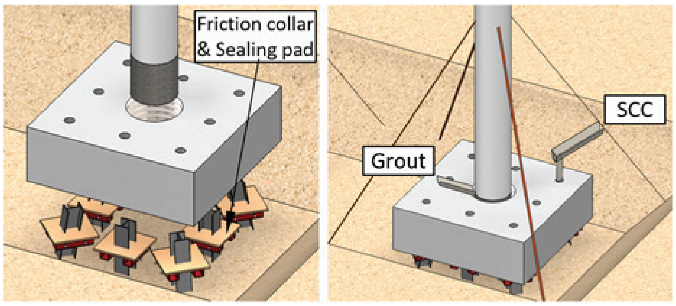
Research Description

Proposed Bridge Column/Footing/Pile System

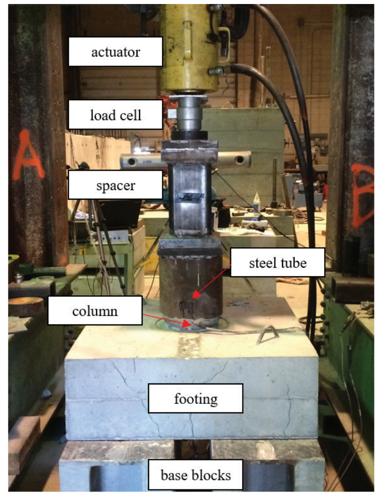
A precast pile cap was used to build the bridge column/footing/pile system for ABC.



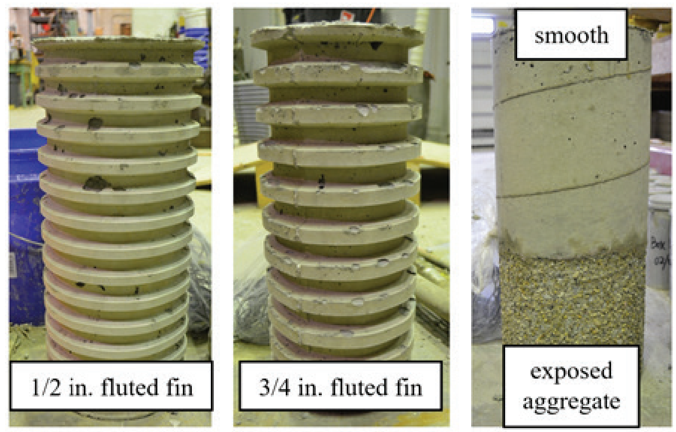
Precast pile cap with preformed sockets



Construction of column/footing/pile system



Test setup for socket connection tests



Four surface conditions used to evaluate socket connection performance

The sockets were created within the footing using corrugated steel pipes (CSPs). The system was assembled by embedding the precast column and steel piles into the sockets using grout and self-consolidating concrete (SCC), respectively. The column socket was constructed to partially penetrate the pile cap, and the pile sockets were made in the shape of a cone and installed through the pile cap.

To construct the system, both vertical and battered steel piles were driven, and then temporary friction collars were affixed to each pile. The precast pile cap was supported on the friction collars, allowing the piles to be extended into the pile sockets. After erecting and bracing the precast column, the sockets were filled with grout and SCC, respectively.

The friction collars were designed to carry the weights of the precast components until the SCC reached adequate strength. Given that, superstructure construction could begin the day after completing the closure pours, at which point the high early-strength grout reached the specified compressive strength of 6,500 psi.

Column Socket Connection Tests

The socket connection test was conducted to help determine the key connection parameters and side shear strength for designing the column socket connection. Eight specimens were tested to investigate the effects of the parameters that most influence the strength:

- Surface texture along the embedded length of the precast column
- Clearance between the embedded member and the CSP
- Loading type

Each specimen consisted of a short precast column segment and precast foundation. The surface textures of the column segment specimens included an exposed aggregate finish, a 0.5 in. fluted fin, a 0.75 in. fluted fin, and a smooth finish as a reference.

Two clearances, of 1.5 in. and 3 in., were reserved around the column segments. Compressive force was applied to the top of the column segment so that side shear strength could be evaluated by loading the column until it experienced a sliding failure with respect to the foundation. Four specimens were tested using monotonic loading; whereas, the other four specimens were subjected to cyclic loading.

Outdoor System Test

An outdoor system test was conducted to investigate the performance of the proposed substructure assembly. The unique features of the outdoor system test included the following:

- Incorporation of foundation flexibility in virgin soil
- Use of steel H-piles
- Inclusion of battered piles
- Use of large vertical loads in an outdoor lateral load test

A half-scale test unit was constructed at an outdoor location consisting predominantly of cohesive soil.

The test unit incorporated a precast column, a precast pile cap, and eight steel H-piles, including a battered pile

Assembled half-scale test unit for outdoor system test

in each of the four corners of the pile cap at a slope of 1:6 (horizontal to vertical).

A partially penetrated socket and eight fully penetrated sockets were designed for the pile cap. The column end was roughened to an exposed aggregate finish and embedded into the column socket connection over a length equal to the column diameter. Consistent with current practice, the pile embedment length into the pile cap was 1.5 times the depth of the pile.

The outdoor system subassembly unit was tested under different combinations of vertical and lateral loads. A vertical reaction frame and a lateral reaction column were constructed next to the test unit to apply the vertical and lateral loads simultaneously. For the first two phases, the lateral load was applied at the top of the column to produce a high overturning moment-to-lateral load ratio. For the remainder of the testing phases, the lateral load was applied to the pile cap to fully examine the pile socket connections.

Key Findings

Column Socket Connection Tests

- With the exception of the specimen with the smooth column surface, the specimens provided significant and comparable side shear strengths against the axial loads applied to the column segments.
- The specimens consisted of column segments with deep amplitude surface textures exhibited softer connection responses. A thicker grout closure pour (resulting from wider CSP-to-column clearance) also marginally reduced the stiffness of the socket connection.
- Considering the cost and ease of construction, exposed aggregate for embedded member surface preparation, standard CSP, and high-strength grout are recommended for effectively establishing socket connections.
- For connections following the recommended details, the side shear stress limitations of 1,000 psi and 700 psi are suggested for the column-to-grout interface and CSP-to-surrounding concrete interface, respectively.

Outdoor System Test

- The test unit modeling the proposed bridge column/footing/pile system produced dependable performance when subjected to the factored design loads. There was no damage to the column socket or pile socket connections at this stage of testing.
- When the lateral force was gradually increased to exceed the design demand, damage occurred at the column base due to plastification, as expected given the design, and limited crushing or spalling was observed in the column socket connection with no damage occurring to the pile connections. This confirmed the adequacy of all ABC connections. This observation also confirmed that performance of the prefabricated column-pile cap-pile system was at least as good as, if not better than, that of a comparable, conventional, cast-in-place system.
- For the column socket connection, the embedment length equal to the column diameter is sufficient to fully develop the column flexural capacity; whereas, the pile embedment length of 1.5 times the depth of the H-pile is recommended to maintain fixity for the pile socket connection.
- Foundation flexibility produced a significant effect on system response. About 40% of the column top lateral displacement was due to foundation flexibility prior to developing flexural inelastic strains in the column critical region. As inelastic action progressed in the column, the percentage contribution of foundation flexibility toward the column top lateral displacement was reduced to about 10%.

Implementation Readiness and Benefits

In this study, the performance of a bridge column/footing/pile system using ABC techniques was successfully verified. The constructability advantages of the prefabricated column-pile cap-pile system are that it is quick and simple to build, as demonstrated through the outdoor test. Using friction collars, SCC, and grout with desirable characteristics, the assembly of the proposed column-pile cap-pile system can be completed within a day after driving the piles.

As a result, the bridge substructure assembly involving prefabricated components can take place shortly after driving the foundation piles. Consequently, the proposed ABC approach for the substructure can reduce construction delays, serviceability problems, and costs, while ensuring quality construction.