AN EARTHQUAKE-RESISTANT PRECAST BRIDGE SUBSTRUCTURE SYSTEM UTILIZING SOCKET CONNECTIONS

Z. Cheng¹, S. Sritharan² and J. Ashlock³

ABSTRACT

To promote the use of precast components in construction of bridge substructures, an earthquake-resistant bridge substructure system that consists of a precast column, a precast pile cap, and steel H-piles has been conceptualized. The key innovations of the system are the column socket and the pile sockets on the pile cap, which are accomplished using commercially available corrugated steel pipe (CSP). By embedding precast column and steel H-piles into these sockets with grout/concrete closure pours, a bridge substructure can be completed over a short construction period with ample installation tolerances. The column and the H-piles are embedded into the sockets with sufficient embedment lengths, and the CSPs ensure adequate confinements within the connections. Thus, when column plastic hinge forms during a seismic event, the socket connections would remain essentially elastic with minimal damage. Two experimental investigations were planned to validate the connections and the performance of the substructure system. First, a series of socket connection tests have been conducted to study the behavior of column socket connection under vertical loads and the optimal connection details. Second, a half-scale test unit consisting of the substructure and foundation soils is under construction at an outdoor location. This test unit will be subjected to a combination of vertical and lateral loads. This paper summarizes: (1) a detailed introduction of the precast bridge substructure system; and (2) the findings from the experimental investigations.

¹Graduate Research Assistant, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011 (email: zcheng@iastate.edu)
²Wilkinson Chair Professor, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011
³Richard L. Handy Associate Professor, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011

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Z. Cheng\textsuperscript{1}, S. Sritharan\textsuperscript{2} and J. Ashlock\textsuperscript{3}

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To promote the use of precast components in construction of bridge substructures, an earthquake-resistant bridge substructure system that consists of a precast column, a precast pile cap, and steel H-piles has been conceptualized. The key innovations of the system are the column socket and the pile sockets on the pile cap, which are accomplished using commercially available corrugated steel pipe (CSP). By embedding precast column and steel H-piles into these sockets with grout/concrete closure pours, a bridge substructure can be completed over a short construction period with ample installation tolerances. The column and the H-piles are embedded into the sockets with sufficient embedment lengths, and the CSPs ensure adequate confinements within the connections. Thus, when column plastic hinge forms during a seismic event, the socket connections would remain essentially elastic with minimal damage. Two experimental investigations were planned to validate the connections and the performance of the substructure system. First, a series of socket connection tests have been conducted to study the behavior of column socket connection under vertical loads and the optimal connection details. Second, a half-scale test unit consisting of the substructure and foundation soils is under construction at an outdoor location. This test unit will be subjected to a combination of vertical and lateral loads. This paper summarizes: (1) a detailed introduction of the precast bridge substructure system; and (2) the findings from the experimental investigations.

Introduction

Use of precast components in bridge industry is a proven methodology with several benefits over traditional cast-in-place (CIP) construction, which include fast project delivery, improved construction quality, low life-cycle cost, minimal environmental impact, and reduced traffic delay.

\textsuperscript{1}Graduate Research Assistant, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011 (email: zcheng@iastate.edu)
\textsuperscript{2}Wilkinson Chair Professor, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011
\textsuperscript{3}Richard L. Handy Associate Professor, Dept. of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA 50011

disruption. Precast components have been widely used for bridge superstructures, and many state DOTs have utilized precast bent cap and precast column in the construction of bridge substructure [1]. However, due to the lack of reliable connections, current practices still require the pile cap to be CIP. Considering that the seismic design of bridges promote formation of plastic hinges in columns while capacity-protecting (CP) other regions, including connections, so that they will remain essentially elastic when the column reaches its overstrength capacity. This approach needs to be satisfied when precast bridge substructures are implemented. Considering the force transfer mechanisms, the connections that have potential to establish a CP connection can be classified as a bar coupler, grouted duct, pocket connection, or socket connection [2]. Among these types of connections, the socket connection offers ample installation tolerances and simplified the construction procedure. Hence, to promote the use of precast components in routine bridge substructure construction, a new precast bridge substructure system that employs a precast pile cap was developed. Through the use of sockets that are reserved on the pile cap, the system can be constructed by insert the piles and precast column into these sockets and establishing the connections with in-situ concrete/grout in the sockets.

The performance of the precast bridge substructure system was explored experimentally. First, a series of socket connection tests was conducted to investigate the behavior of the column socket connection in the sustaining axial load resulting from gravity effects. Second, a system test is being performed at an outdoor test site in order to adequately account for the soil-foundation-structure interaction and quantify the overall system performance. A half-scale test unit is under construction, which will be tested under a combination of vertical and lateral loads. This paper summarizes the experimental investigation on the development of the precast bridge substructure system. Specific areas of interest include: (1) a detailed introduction of the precast bridge substructure system; and (2) the findings from the experimental investigations.

**Precast Bridge Substructure System**

A single column bent that consists of a bent cap, a column, a pile cap, and driven piles has been widely used as bridge substructure. Current practice [1] and recent research [3] show the feasibility of constructing such a bent with a precast bent cap and a precast column. However, the current practice still uses a CIP pile cap. To utilize precast components for the entire substructure, a bridge substructure system employing precast pile cap has been developed. The key innovations of the system are the column socket and the pile sockets that are reserved on the top and bottom of the precast pile cap, as illustrated in Fig. 1. By embedding bottom end of a precast column and top of steel H-piles into these sockets, followed grout/concrete closure pours, a single column bent can be constructed without CIP members. The sockets are routinely accomplished using commercially available corrugate steel pipes (CSPs) due to their low cost and variability in sizes. In addition to serving as stay-in-place formwork, CSPs offer confinement effect for the connection and their corrugations support a robust load transfer mechanism. The column socket is constructed to partially penetrate the pile cap from the top. Hence, the bottom-layer reinforcing bars of the pile cap is placed underneath the socket. The pile sockets penetrate through the pile cap for conducting closure pours, and the upper portion of these sockets are made in the shape of cone. This configuration allows the top-layer reinforcing bars to be placed through the sockets without notches on the CSPs as this would unnecessarily complicate the construction.
For constructing the system, steel H-piles are first installed, which employs template to maintain the piles in proper position and alignment. Then temporary friction collars are affixed around each pile (Fig. 2a), on which the precast pile cap is supported. At this stage, top of all H-piles are positioned into the respective pile sockets. The use of friction collars offers the feasibility of conducting construction in poor ground conditions and achieves better erection tolerance control. After erecting the precast column with an intentionally roughed end, as shown in Fig 2b, the column, the pile cap, and the piles are connected together by filling the column socket and the pile sockets with grout and self-consolidating concrete (SCC), respectively. One particular type of grout with desirable properties such as high-early-strength, fluid consistency, extended working time, and non-shrink is chosen for securing the column socket. The chosen grout can reach a specified compressive strength of 4000 psi in 8 hours (6500 psi in 1 day), and the friction collars are designed to carry the weights of pile cap, column, and upper structural components before SCC reaches the adequate strength. Therefore, the construction of the superstructure can begin on the day after completing closure pours. When SCC reaches the specified short-term strength, the friction collars can be removed and reuse.

Socket Connection Tests

When connecting to precast pile cap, the precast column should not experience any sliding with respect to the pile cap. In other words, the column socket connection should have adequate strength to transfer the gravity load. The axial strength of the partially penetrated column socket connection results from side shear acting along the embedded column and tipping at the base of the column. Given the potential difference in required displacements to develop significant strength from side shear and tipping, the connection shall be conservatively designed.
relying on side shear only. However, for the precast column socket connection using CSP and grout closure pour, there is no guideline available as to how the connection parameters (e.g., embedded column surface roughness and the clearance between the column and CSP) would affect the connection performance and how the connection should be detailed for a given axial load. Addressing these issues, the socket connection tests were conducted to investigate the side shear behavior in the column socket connection and develop the optimal connection design.

**Testing Matrix**

For the column socket connection constructed with CSP and grout closure pour, the axial load resistance resulting from side shear depends on a number of parameters. The parameters that most influence side shear strength include: (1) strength of grout used for closure pour, (2) corrugation pattern in CSP, (3) embedded column surface roughness, and (4) clearance between column and CSP that is filled by grout. The compressive strength of high-strength grout typically reaches 8000 psi or higher at 28 days, and a corrugation pattern of 2-2/3 in. (pitch) × 1/2 in. (depth) is standard for CSP that is appropriate to form sockets for bridge columns ranging from 1.5 ft to 4 ft. The embedded precast column surface is required to be intentionally roughened for ensuring adequate shear transfer between concrete and grout that are cast separately [3]. Different practical methods such as sandblasting, formwork retarder, and bush-hammering can be used for achieving the desired surface finishes. Form liners can also be used if regularized patterns such as fluted fins or saw-tooth shapes are preferred. Sufficient clearances must be provided in the socket to account for cumulative effects of all allowed tolerances. For inserting precast columns, a minimum clearance of 1 in. is required around the perimeter between the column and the socket [4]. The clearance is also controlled by the available size of CSP. Among the aforementioned connection parameters, the grout strength and CSP corrugation pattern are relatively constant in practice. Hence, the socket connection tests were conducted with standard CSPs, typical concrete and grout strength, varied column surface roughness, and different column-to-CSP clearances. As detailed in Table 1, the surface roughness included smooth surface with no treatment, exposed aggregate finish using formwork retarder, and 1/2 in. and 3/4 in. trapezoidal shaped fluted fins made using form liners. With 1/2 in. and 3/4 in. fluted fins, the specified dimensions represent the depth of the fin, while the pitch measured from a fin to fin was 1-1/2 in. and 2 in., respectively. Based on the appropriate commercially available CSP for a common size column, two clearances between column and CSP (i.e., 1.5 in. and 3 in.) were tested. In addition, the type of loading was also used as a variable. The first four specimens were tested using monotonic loading, whereas the four units were subjected to cyclic loading. The cyclic loading consisted of two phases: one force cycle per step at 40 kips increment, followed by displacement controlled cycles with three cycles per step.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Measured column concrete strength (psi)</th>
<th>Measured footing concrete strength (psi)</th>
<th>Measured Grout strength (psi)</th>
<th>Column surface roughness</th>
<th>Column-to-CSP clearance (in.)</th>
<th>Loading type</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1G1M</td>
<td>5362</td>
<td>5362</td>
<td>8062</td>
<td>1/2 in. fluted fin</td>
<td>1.5</td>
<td>monotonic</td>
</tr>
<tr>
<td>Specimen</td>
<td>CSP Dimensions</td>
<td>Connection Type</td>
<td>Surface Finish</td>
<td>Ductility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
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<td>---------------</td>
<td>-----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2G1M</td>
<td>5362 x 5362 x 8150</td>
<td>3/4 in. fluted fin</td>
<td>1.5</td>
<td>monotonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EG1M</td>
<td>5362 x 5362 x 8084</td>
<td>exposed aggregate</td>
<td>1.5</td>
<td>monotonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2G2M</td>
<td>5362 x 5362 x 8203</td>
<td>3/4 in. fluted fin</td>
<td>3</td>
<td>monotonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EG1C</td>
<td>5715 x 5362 x 7904</td>
<td>exposed aggregate</td>
<td>1.5</td>
<td>cyclic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1G1C</td>
<td>5715 x 5362 x 8035</td>
<td>1/2 in. fluted fin</td>
<td>1.5</td>
<td>cyclic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG1C</td>
<td>5715 x 5362 x 8172</td>
<td>smooth</td>
<td>1.5</td>
<td>cyclic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F1G2C</td>
<td>5715 x 5362 x 8172</td>
<td>1/2 in. fluted fin</td>
<td>3</td>
<td>cyclic</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Test Specimens**

Each test specimen, as shown in Fig. 3a, consisted of a short precast column and a precast footing. After inserting the column into the socket that was preformed using a standard CSP, the connection for each specimen was established by placing grout. After trying several grouts, a particular grout was used due to its desirable properties such as high-early-strength, high-strength, fluid consistency, extended working time, and non-shrink. Columns were constructed with four different surface roughness as shown in Fig. 3b, which depicts the 1/2 in. and 3/4 in. fluted fins, smooth surface, and exposed aggregate surface finish. The 12 in. and 15 in. diameter CSPs with the corrugation pattern of 2-2/3 in. × 1/2 in. were used to create 1.5 in. and 3 in. clearances for grouting. An oversize blockout was formed under the socket in each footing to eliminate the column from bearing on the foundation. To prevent the columns above the footing from experiencing damage due to compression failure, they were confined by a steel tube with grout infill. Using a hydraulic actuator that was attached to a reaction frame, the vertical downward forces were applied on the top of the column until a sliding failure was observed.

![Diagram of test specimen](image)

**Test Results**

During tests, each specimen began to resist load in an elastic manner, reached its maximum resistance with some nonlinearity associated with the response, and then exhibited considerable ductility beyond the peak strength. Following the peak strength, some softening in the response was observed. Fig. 4 depicts the applied vertical force versus the relative displacement between
the column and the footing (CF displacement), which represent the overall response of each specimen. All specimens, except the one with smooth column surface, reached the peak strength in the range of 264 kips to 329 kips, which is equivalent to 0.75 to 0.94\(A_g f'_c\) (where \(A_g\) is column gross area and \(f'_c\) is measured column concrete compressive strength). In bridge columns, it can be conservatively assumed that the axial load ratio will not exceed 0.30. For this level of axial load, it is important to realize that a roughened column surface will ensure an elastic response for the connection without exhibiting any distress.

![Figure 4. Applied axial force versus CF displacement response](image)

As seen in Fig. 4, the columns with roughened surface provided adequate bond strength between the grout and surface of the embedded column, but the specimens exhibited different force-CF displacement responses. The CF displacements consisted of the sliding at the column-to-grout closure pour interface (CG displacement), the sliding at the grout closure pour-to-footing interface (GF displacement), and the deformation within the grout itself (\(\Delta_{\text{grout}}\)) especially when 3 in. thick grout closure pour was included. Test data indicated that all specimens exhibited comparable GF displacement responses before reaching the peak strength. Hence, the differences in overall connection responses seen in Fig. 4 are the result of CG displacement and \(\Delta_{\text{grout}}\). Fig. 5a plots the vertical forces versus CG displacements for the specimens with 1.5 in. clearance, but with different column surface roughness. This plot indicates that the deeper amplitude of 1/2 in. and 3/4 in. fluted fins could soften the connection responses. Comparing the force versus CF displacement responses for Specimens F1G1C and F1G2C, which have the same column surface roughness but different grout closure pour thickness corresponding to column-to-CSP clearance, Specimen F1G2C showed a softer overall connection response than specimen F1G1C, but the two specimens exhibited the same force versus CG displacement responses. Therefore, the wider column-to-CSP clearance that induced significant \(\Delta_{\text{grout}}\) was proven to soften the connection responses. Regarding the loading type, Fig. 5b presents a comparison of the specimen responses with the same connection parameters but for different load types. For the specimens with exposed aggregate finish, no cumulative damage was caused by the cyclic loading until reaching 150 kips, which was approximately 50% of the peak strength. However, the cyclic loading caused significant strength degradation for the specimen consisting of a column with 1/2 in. fluted fins.
Figure 5. (a) Impact of different column surface roughness and (b) Impact of cyclic loading

Considering both the performance and constructability, the embedded portion of the column may be adequately prepared using exposed aggregate finish, which can be easily accomplished using formwork retarder or an appropriate form liner that can ensure a similar texture. Both 1.5 in. and 3 in. clearance between the column and the CSP ensure that the socket connection sustains vertical loads, but 3 in. clearance that caused thicker grout closure pour reduced the stiffness of the socket connection. Therefore, a 1.5 in clearance or relatively smaller clearance than 3 in. is recommended.

System Test

After the socket connection tests, a system test is being conducted to investigate the performance of the entire precast substructure system. Considering the effect of soil-foundation-structure interaction, the test unit with a driven pile foundation will be tested at an outdoor location.

Test Unit

A half-scale test unit was chosen to represent the substructure in a typical pretensioned prestressed concrete beam bridge with frame piers. The test unit consisted of a 6 ft x 6 ft x 2 ft precast pile cap with preformed sockets and a 1.5 ft diameter precast column, along with eight steel driven piles. The sockets for the column and piles were preformed with a 21 in. diameter CSP and eight 15 in. diameter CSPs, respectively. The column socket was constructed as a partially penetrated socket with the depth of 19 in. In the pile sockets, stay-in-place steel pipe diameter reducers were installed to make a cone shape for the upper portion of these sockets, as shown in Fig. 6a. To verify the construction option of reusing these reducers, three of the eight cones were manufactured with the diameter smaller than the pipes, thus the reducers can be taken out through the pipe for reuse. The height of the precast column was decided to be 6 ft, which resulted in a flexure-critical column with a height to depth ratio of 4. The transverse reinforcement in the column was arranged following the guidelines for column confinement [6], and the reinforcement was extended to the portion of the column that would be inserted into the socket. Based on the findings from the socket connection tests and previous research [7], the column embedded length into the socket was chosen to be 18 in., which is equivalent to the diameter of the column. The surface of the embedded portion was treated to exposed aggregate finish using formwork retarder. For applying the combination of vertical and lateral loads, a
loading block was added to the top of the column. The column has been constructed upside down, as shown in Fig. 6b. The prototype driven piles were scaled to W6×20 sections in the test unit. The piles were embedded 9 in. into the pile sockets, which represented the embedment length of 1.5 ft in the prototype substructure as per the current practices.

Figure 6. (a) Pile cap before concrete pour and (b) Precast column with loading block

Load Protocol

A load protocol for the system test consists of three phases. Phase I will be conducted to verify the strength of the system at the strength limit states. A combination of vertical and lateral loads will be applied on the top of column. After the first phase of the test, the test unit will be subjected to a constant vertical load that will correspond to 15% the column axial load capacity and force-controlled cyclic lateral loads. Once the test unit exhibits nonlinearity associated with the response, displacement-controlled cyclic loading will be used until a plastic hinge fully develop at the column base adjacent to the pile cap. According to the analysis performed on a grillage finite element model, when the column plastic hinge forms in the test unit, the displacement of pile cap will be around 1/4 in., and the pile socket connections will experience relatively small bending moments. To fully test the connections and investigate the soil-foundation-structure interaction, the Phase III will be conducted by applying the lateral loads to the pile cap directly. Eight #8 headed bars were partially embedded in the pile cap. A CIP loading block will be constructed encasing the column base and headed bars for attaching the actuator as shown in Fig. 7. Thus, the Phase III can be performed until failure occurred in substructure and/or soil.

Figure 7. Location of lateral actuator for system test
Test Setup

To conduct all phases of the system test, a vertical reaction frame and a lateral reaction column were constructed as shown in Fig. 8a. The vertical reaction frame consists of four HP14x73 anchor piles that are driven 50 ft into the ground. A main reaction beam, which is shown as the green beam in Fig. 8a, will be attached to the anchor piles through clamping beams and steel rods. Through the main reaction beam, four hydraulic jacks will be used to apply the downward vertical loads to the test unit. A single concave slider will be installed on the top loading block to isolate translation and rotation, while transmitting loads from the main reaction beam to the top of column, and thus the vertical loads can be applied stably when the column drifts under a lateral load. The lateral reaction column is constructed by post-tensioning precast hollow segments on a 45 ft deep, 6 ft diameter drilled shaft foundation. As shown in Fig. 9b, four vertical holes were reserved at the corners of segments. Hence, the 1-3/4 in. diameter post-tensioning bars will be placed through the vertical holes, and connected with the bars that were anchored into the drilled shaft for post-tensioning. Each segment has the preformed hole pattern on sides such that the actuator can be attached at various height during different phases of the test.

![vertical reaction frame](image1)
![later reaction column](image2)

Figure 8. (a) A schematic of testing setup and (b) Precast segments for lateral reaction column

Conclusions

In recent years, there has been interest in using prefabricated component for entire bridge substructure for accelerating bridge construction. The socket connection that is preformed using standard CSP has been identified as a viable means to construct precast bridge substructure. Thus, to investigate the overall performance of the system as well as the connection behavior, the experimental investigations were conducted on a precast bridge substructure system. The socket connection tests have been conducted to evaluate the side shear behavior in proposed column socket connection and optimize the connection design. A test unit for the system test is being constructed and will be tested at an outdoor location in December 2017. Based on the completed tasks of the project, the following conclusion can be drawn:

- The precast bridge substructure system with socket connections provides the potential to significantly reduce the construction time while offering larger construction tolerances than other methods that are developed for precast bridge substructure.
- All specimens of the socket connection tests, except the one with smooth column surface, reached the peak strengths that were equivalent to axial load ratio above 0.75. Hence, the socket connections with roughened column surface would provide satisfactory
connection to sustain vertical loads used in routine design practice.

- The connection consisting of the columns with deeper amplitudes for the surface roughness (i.e., 1/2 in. and 3/4 in. fluted fins) exhibited softer connection response compared to the one with exposed aggregate surface. The thicker grout closure pour also reduced the stiffness of the socket connection. Therefore, the column surface finish of exposed aggregate finish and 1.5 in clearance or relatively smaller clearance than 3 in. is recommended for the design of the column socket connection.

In addition to the above finding, the presentation will also summarize the results from the system test.

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