Foundation Reuse in Accelerated Bridge Construction

Nathan T. Davis, M.ASCE1; Ehssan Hoomaan, S.M.ASCE2; Anil K. Agrawal, M.ASCE3; Masoud Sanayei, M.ASCE4; and Farrokh “Frank” Jalinoos, M.ASCE5

Abstract: When an existing bridge is being considered for replacement due to a deteriorated or obsolete superstructure, the foundation may still have significant functional value. Reuse of these foundations during bridge replacement or widening can present significant cost and time savings over constructing new elements. The potential time savings associated with foundation reuse can reduce mobility impacts, a key goal of accelerated bridge construction (ABC), and the cost savings can increase the economic viability and sustainability of an ABC bridge replacement project. However, existing foundations may have uncertain material properties, geometry, or details that impact the risks associated with reuse. Unlike a new foundation, an existing foundation may have been damaged, may not have sufficient capacity, and may have limited remaining service life due to deterioration. Assessment of these issues, possible foundation-strengthening measures, and innovative approaches to optimize loading are discussed in this paper. An analysis of an ABC database is performed to examine the current role of foundation reuse in ABC projects. This paper presents some key findings identified through various research projects related to foundation reuse. Six case examples are presented in which foundations were reused or considered for reuse during a bridge replacement project. DOI: 10.1061/(ASCE)BE.1943-5592.0001455. © 2019 American Society of Civil Engineers.

Author keywords: Foundation reuse; Accelerated bridge construction; Maintenance; Decision making; Retrofitting.

Introduction

As of 2017, there were 54,560 bridges in the United States in poor condition (FHWA 2018b). The renewal, widening, or replacement of these deficient bridges puts increased financial strain on bridge owners and stakeholders. For many deficient bridges in both rural and urban areas, closure for any significant length of time can cause traffic delays, block access for emergency vehicles, impact local business interests, and create additional costs related to traffic rerouting. In recent years, accelerated bridge construction (ABC) has gained popularity as a method for controlling the impacts on users by drastically shortening the on-site construction time and the mobility impacts. ABC refers to a variety of planning, design, or construction techniques used to reduce construction time when building new bridges or replacing old bridges (Culmo 2011; FHWA 2018a). One of the most common applications for ABC is limiting mobility impacts for bridge replacement projects on high-traffic or important routes where a complete or partial closure of a bridge may impact the larger transportation network. In some cases, bridges requiring rehabilitation or replacement are founded on substructures and foundations that still have significant functional value. The reuse of these elements presents substantial cost and time savings due to the decreased amount of construction required.

Initial research into foundation reuse was focused on the reuse of building foundations in crowded urban sites. A European Union project called Reuse of Foundation for Urban Sites (RuFUS) produced a best practice handbook (Butcher et al. 2006) to provide technical guidance on foundation reuse. CIRIA followed a year later with a guide (Chapman et al. 2007) intended provide an overview of the risks and strategies behind foundation reuse. Strauss et al. (2007) discussed the drivers that impact the frequency of building foundation reuse in the United States and the use of Sustainable Project Appraisal Routine (SPeAR) diagrams that visually convey the favorable influence of the identified drivers.

The Federal Highway Administration (FHWA) Foundation Characterization Program (FCP) held a workshop in early 2013 (Schaefer and Jalinoos 2013) on the characterization of bridge foundations. This workshop identified many issues surrounding the analysis of existing foundations but was not explicitly focused on reuse. In early 2014, the FCP held a workshop (Collin and Jalinoos 2014) specifically focused on bridge foundation reuse.

The first major research project to explicitly focus and formally survey agencies on the reuse of bridge foundations culminated in the National Cooperative Highway Research Program (NCHRP) Synthesis 505, titled Current Practices and Guidelines for the Reuse of Bridge Foundations (Boeckmann and Loehr 2017). This report included survey responses from 45 US state transportation agencies and eight Canadian transportation agencies regarding their reuse practices and guidelines. Of the 53 responding agencies, 51 cited experience with foundation reuse. Fifty respondents provided situations where bridge foundation reuse had occurred. The answers to this survey indicated that the motivations for reuse included bridge widening, superstructure replacement, seismic retrofit, increases to clearance, bridge repurposing, scour retrofit, and retrofit to a cantilever retaining wall, as shown in Fig. 1.

The FHWA report Foundation Reuse for Highway Bridges (Agrawal et al. 2018) provided an in-depth discussion of the technical aspects of evaluation and potential retrofit of bridge foundations. In this report, 15 case studies across the United States and

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Canada were used to highlight common issues and technical solutions. The report provided a discussion of the benefits and challenges associated with foundation reuse for ABC projects. A sample of ABC projects with substantial substructure and foundation work taken from the Florida International University (FIU) ABC database (FIU 2017) was provided that details the type of foundation work involved. Aktan and Attanayake (2015) published a manual for the Michigan DOT (MDOT) on ABC construction techniques that included significant discussion on the installation of new foundation elements in the vicinity of existing foundation elements.

**Definition of Foundation Reuse**

Agrawal et al. (2018) provided the following definition of bridge foundation reuse: “use of an existing foundation or substructure of a bridge, in whole or in part, when the existing foundation has been evaluated for new loads,” where foundation is used to describe all components below the ground level, and substructure describes aboveground components, like piers, abutments, pier caps, and columns. This distinction is useful when discussing reuse because available inspection methods and typical concerns can vary between above- and belowground elements.

Butcher et al. (2006) considered four available foundation reconstruction options: complete reuse, partial reuse, complete replacement, and removal and replacement. This categorization scheme was adopted by Collin and Jalinoos (2014) to better fit with situations observed in bridge foundation reuse. Fig. 2 illustrates the foundation options available when reconstructing a bridge superstructure.

Options 1 and 2 are considered foundation reconstruction, where a new foundation is built. Options 3 and 4 are considered foundation reuse, where all or portions of existing foundations are reused. The options are not necessarily mutually exclusive because one replacement project may involve multiple abutments and piers, with some saved and others not. A description of the reuse options, Options 3 and 4, are provided in the following.

![Diagram of foundation options](Image)

**Fig. 1.** Applications for foundation reuse. (Data from Boeckmann and Loehr 2017.)

**Fig. 2.** Foundation reconstruction options. (Reprinted from Jalinoos 2015.)
Option 3 alternatives involve reuse of the existing foundation with a new superstructure that can be lifted, slid, or transported into place. This approach allows for preservation of the original right of way (ROW) and historical appearance, and reduces the amount of new materials required. Option 3 alternatives may involve patching spalls, chloride extraction, or other minor repair work to substructure elements to maintain their functionality but that are more or less used in their existing condition. The primary mobility impacts for Option 3 bridges occur during superstructure replacement, which can be limited to a very short window using conventional heavy-lifting equipment (CHLE), self-propelled modular transporters (SPMTs), or slide-in bridge construction (SIBC). Option 3 alternatives may be suitable for deck widening if there is sufficient reserve capacity in the substructure or foundation for increased loads, or if innovative materials are used for the bridge deck to reduce loading on reused components.

Option 4 alternatives reuse the existing foundation enhanced with major repair, retrofit, or strengthening. Strengthening or retrofit can include any changes made to the system that improve the capacity or durability of existing elements, such as underpinning or strengthening with new piles or shafts, encasement of piers or piles with concrete, wrapping of elements with fiber-reinforced polymer (FRP) or PVC, installation of new piles or shafts for a widened footprint, installation of additional reinforcement to existing concrete sections, ground improvement near existing elements to increase capacity, installation of additional piers, or installation of scour protection. These activities can be performed while the bridge is in service, limiting mobility impacts. Option 4 may include seismic retrofits to existing pier columns, a relatively mature field of bridge repair in high-seismic zones.

Motivations for Foundation Reuse

Collin and Jalinoos (2014) reported the following nine drivers for foundation reuse in bridge projects that were identified by presenters and speakers at a Transportation Research Board (TRB) workshop:

- Asset management: Existing elements still have functional value;
- Technical drivers: Installation of new elements may be difficult;
- Time savings: Minimize bridge closure by limiting amount of construction;
- Economic drivers: Real cost savings and user cost savings;
- Efficiency: Lower costs and shortened construction means more deficient bridges can be replaced;
- Past performance: Foundation has been load tested by past loading;
- Environmental benefits: Lower material usage and waste generation, lower construction impact in sensitive areas (e.g., rivers, wetlands);
- Sustainability issues: Lower material usage and waste generation; and
- Historic preservation: Reuse allows preservation of historical bridge features.

One of these drivers for foundation reuse is sustainability issues. Sustainability succinctly sums up many of the benefits that can be derived from foundation reuse because many of the drivers behind foundation can be considered as contributing to a project’s sustainability. Sustainability, as defined by the FHWA Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) program (FHWA 2017), consists of a triple bottom line of outcomes: social, economic, and environmental. The goal of viewing projects from a sustainability perspective is to meet the continuing social needs of users at a minimum cost while minimizing the use of natural resources. In the survey performed in NCHRP Synthesis 505 (Boeckmann and Loehr 2017), the 51 respondents who reported experience were also asked to provide the situations and needs that had motivated foundation reuse. The responses generally align with other drivers discussed in the workshop, as shown in Fig. 3. The workshop responses can all be considered as contributing to at least one of the triple bottom line items, as shown in the following:

- Social:
  - accelerated construction;
  - project schedule;
  - right-of-way constraints; and
  - emergency repairs.
- Economic:
  - economic considerations;
  - constructability;
  - historic preservation; and
  - utility conflicts.
- Environmental:
  - environmental and permitting; and
  - bridge repurposing.

Foundation Reuse in ABC Projects

The decision to use ABC is typically driven by a desire to lessen impacts on traffic, deal with constructibility issues, avoid use of
temporary structures, avoid weather-related delays, and utilize short construction seasons (Culmo 2011). Since mobility impacts and construction time are the key concerns when pursuing ABC construction projects, ABC projects are gauged by two different time metrics: on-site construction time and mobility impact time. ABC projects are frequently categorized by mobility impact time, with projects assigned one of five tiers (Culmo 2011; FHWA 2018a; FIU 2017). Tier 1 projects have the shortest traffic impacts (less than a day) and Tier 5 have the largest mobility impacts (greater than 3 months). FIU (2017) uses a similar six-tier system, with an additional differentiation between less than 1 month of impacts and 1–3 months of impacts. For clarity, this system was adapted to have a five tiers (Culmo 2011; FHWA 2018a). The reduction of on-site construction is a driver for ABC because it reduces the potential for user impacts, on-site safety issues, and costs related to construction activities. Also, Jalinoos et al. (2017) reviewed the application of foundation reuse in ABC projects.

The FIU University Transportation Center (UTC) ABC project database (FIU 2017) includes 111 ABC projects from around the country. This database provides information on the superstructure type, installation method used, closure time (and corresponding tier), and cost information for select projects. The case examples that make up the database are provided to the database by owners, stakeholders, and design engineers, so they are not a random sample of ABC projects. Table 1 presents a summary of the foundation replacement options used for the 111 case examples in the ABC database (FIU 2017). This information is not directly provided by the database and was assembled from the descriptions provided of the construction sequence. Fourteen of the case examples in the FIU database represent new construction, where there was no existing bridge or foundations to consider for reuse. Another nine of the case examples represent a deck replacement. The remaining 88 case examples in the database represent reconstruction of an existing bridge.

Table 1 shows that 54 of the 88 (61%) reconstruction projects were Option 2 projects, where the original alignment was maintained without reuse, and 20 of the 88 (23%) reconstruction projects involved foundation reuse, with (Option 4) or without (Option 3) strengthening. More than half of the Option 2 case examples took longer than a month to complete, with many of the longer projects requiring demolition of the existing bridge prior to installation of new abutment walls, piles, drilled shafts, footings, and micropiles, among other things. Thirteen of the Option 2 case examples, however, were performed in less than 3 days using rapid foundation construction, construction of the foundation while the bridge was in service, or construction of the foundation during off-peak lane closures. Overall, it can be noted from the database that many Option 2 bridges saw significant on-site construction time and mobility impacts associated with replacement foundation installation. Some Option 1 examples avoided large mobility impacts by constructing the new bridge prior to closing the existing one, but many of these bridges also saw significant mobility impacts during construction. On the other hand, only 2 of the 20 reuse examples impacted user mobility for greater than 3 months, with both being Option 4 projects where the bridge was closed during foundation strengthening. It is unclear if foundation reuse was feasible or considered for many of the Option 1 or Option 2 case examples.

### Reuse Decision Model

A reuse decision model was proposed by Agrawal et al. (2018) that considered the major portions of the decision-making process for projects considering foundation reuse. The components of the decision-making process are as follows:

- desk study;
- assessment of the existing foundation integrity, durability, and capacity;
- analysis of scour and hazard vulnerability;
- assessing constructability of proposed alternatives;
- environmental impacts assessment (EIA);
- risk analysis of proposed alternatives;
- life-cycle cost analysis (LCCA) of available options; and
- alternative selection.

The desk study and integrity, durability, and capacity assessments are the aspects of the decision model that relate to evaluating the existing bridge conditions and are discussed in the next section. Analysis of scour and hazard vulnerability and the EIA are standard components of bridge foundation construction and are applicable to reuse investigations as well. Agrawal et al. (2018) outlined a risk management process (RMP) that has four phases: identification of risks, assessment of identified risks, development of risk response, and monitoring of identified risks. A life-cycle cost estimation procedure was outlined that converts future costs to present costs using the discount rate and accounts for uncertain and probabilistic costs. An important part of the LCCA that is extremely beneficial for ABC projects is accounting for both user and agency costs. Agency costs refer to direct outlays related to construction, while user costs provide a monetary measure of the impact that construction has on the community and typical bridge users. One crucial user cost to consider is the impact of construction on user travel times.

### Assessment

Agrawal et al. (2018) divided the assessment of bridge foundations into four primary components: the desk study, the integrity assessment, the durability assessment, and the capacity assessment. These investigations are not meant to be mutually exclusive, independent, or sequential, but rather provide an overall grouping of the types of assessment that can be performed on a foundation being considered for reuse.

### Desk Study

The desk study consists of gathering design drawings, as-built information, soil boring records and test data, material strength testing, inspection history, and other available information on the existing foundation. Collecting the available data provides an inexpensive first step that can be used to screen foundations where reuse is potentially viable during replacement or expansion. The data collected in the desk study can be utilized during planning the

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**Table 1. Foundation replacement options found in FIU database**

<table>
<thead>
<tr>
<th>ABC tier (length of impact)</th>
<th>Replacement option</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NC</td>
</tr>
<tr>
<td>Tier 1 (less than 1 day)</td>
<td>3</td>
</tr>
<tr>
<td>Tier 2 (1–3 days)</td>
<td>0</td>
</tr>
<tr>
<td>Tier 3 (less than 2 weeks)</td>
<td>1</td>
</tr>
<tr>
<td>Tier 4a (2 weeks to 1 month)</td>
<td>0</td>
</tr>
<tr>
<td>Tier 4b (1–3 months)</td>
<td>5</td>
</tr>
<tr>
<td>Tier 5 (greater than 3 months)</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
</tr>
</tbody>
</table>

Note: 1, 2, 3, 4 = replacement Options 1–4 (Fig. 2); DR = deck replacement; NC = new construction.
level of integrity, durability, and capacity assessment required, and which factors are most important to address.

**Integrity Assessment**

There is a wide range of testing and items that can be considered during the integrity assessment that are used to inform decisions during later assessment phases. Damage and deterioration can be assessed to make decisions on the longevity of the structure. Testing can be used to assess uncertain parameters such as foundation depth, material properties, and subsurface geometry. Field investigation is frequently performed during reuse to help evaluate foundation capacity, settlement potential, geohazards, and slope stability. The level of testing required during a reuse project is primarily driven by engineering judgment that accounts for the requirements of the proposed project. For instance, if a reuse project is expected to reduce loading on the foundation, then a lower level of testing and capacity assessment would be justified than if loading was being increased.

Agrawal et al. (2018) identified three main categories of integrity testing: visual and physical inspection, material sampling and testing, and nondestructive testing (NDT). Visual and physical inspection are commonly utilized for aboveground visible elements including substructures and can often be performed on near-surface foundation elements that can be exposed in test pits. Material sampling and testing is most commonly employed with concrete structures (and on a more limited basis with masonry and timber members) because removal of test samples allows for compressive strength testing, petrographic testing, modulus testing, and testing of the reinforcement strength. NDT technologies are widely used for evaluating concrete structures, and several technologies can provide subsurface information such as pile length, void and crack detection, and wall depth. A summary of some available NDT technologies and their applicability is provided in Table 2.

Another form of NDT is wireline logging performed in a completed core hole or borehole. Wireline logging has the ability to provide a wealth of information on foundation elements above and below the ground surface. A major advantage of this approach is that core holes can be drilled using standard geotechnical equipment prior to superstructure removal or demolition using temporary closure of a single lane of traffic, as shown in Fig. 4.

Extraction of sample cores during drilling allows for continuous sampling of the substructure and foundation elements with elevation, the foundation–soil interface, and the soil directly underneath the existing foundation. Samples extracted from the column can be destructively tested, petrographically analyzed, or otherwise examined as previously mentioned. Once completed, NDT techniques such as those listed in Table 3 can be deployed in the core hole.

Wireline logging using the preceding techniques or other techniques can provide a continuous log of structural properties such as density, wave speed, and shear modulus while allowing voids to be mapped through videography or other techniques. These properties can also be estimated for soil or bedrock directly beneath the foundation element. An example of a continuous log of masonry wall foundation founded on bedrock is provided in Fig. 5.

**Durability Assessment**

Unlike new construction, existing foundations and substructures have already experienced a significant service life and have been exposed to environmental factors that may have impacted their strength or serviceability. While new construction utilizes materials and practices expected to produce a design with a suitable service life, existing substructures and foundations may contain materials or details that are considered substandard by modern practices. The combination of these factors makes durability considerations an important aspect of reuse of an existing foundation and/or substructure. Common durability considerations include corrosion of steel elements, cracking or spalling of reinforced concrete elements, and decay of timber elements. All these potential issues are greatly impacted by the environment at each specific bridge site.

Agrawal et al. (2018) proposed a durability assessment that consists of three main parts: preliminary assessment, field measurements, and service life prediction. The preliminary assessment...
Table 3. Main core hole logging technologies and their uses

<table>
<thead>
<tr>
<th>Logging technology</th>
<th>Measured parameters</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical televiewer (OTV)</td>
<td>Digitally images the inside of core hole wall using an optical camera; records an orientated 360° unwrapped and three-dimensional image of the core hole wall or a digital core</td>
<td>Ideal for air-filled core holes; for water-filled holes, clear water is required; can pick the orientation of microcracks in structural elements or bedrock</td>
</tr>
<tr>
<td>Acoustic televiewer (ATV)</td>
<td>Oriented images inside of the fluid-filled core hole using an acoustic transducer; provides similar imagery as optical televiewer</td>
<td>Requires fluid-filled holes and works in muddy (unclear) water</td>
</tr>
<tr>
<td>Caliper logs (mechanical and acoustic)</td>
<td>Measure the core hole diameter and any change due to voids or washout zones in soil or bedrock</td>
<td>Determines the change in the diameter of the core hole wall and the depth of voids</td>
</tr>
<tr>
<td>Full waveform sonic (FWS) log</td>
<td>Measures compressional (p), shear (s) Stoneley, and tube wave arrivals and amplitude</td>
<td>Along with density logs, elastic (mechanical) property logs can be derived to display shear, bulk, and Young’s moduli and Poisson’s ratio as a function of depth</td>
</tr>
<tr>
<td>Density log (compensated and 4-pi)</td>
<td>Determines material density</td>
<td>Compensated density measures density values as a function of depth; 4-pi density is mostly used to detect defects</td>
</tr>
<tr>
<td>Electrical resistivity logs</td>
<td>Determines electrical resistivity of material at different radii of investigation as well as single-point resistance (SPR) and spontaneous potential (SP)</td>
<td>Can identify areas of high conductivity in concrete or masonry, and possibly rebar corrosion in rebars in concrete</td>
</tr>
<tr>
<td>Electromagnetic induction logs</td>
<td>Measure electromagnetic conductivity at typically two radii of investigation</td>
<td>Can measure areas of high conductivity and steel corrosion</td>
</tr>
<tr>
<td>Thermal neutron log</td>
<td>Measures the amount of hydrogen atoms in a formation</td>
<td>Its main use is in the determination of porosity or presence of moisture</td>
</tr>
<tr>
<td>Gamma log</td>
<td>Measures the amount of gamma radiation produced mainly by isotopes of potassium, thorium, and uranium</td>
<td>Can identify differing concrete mix or concrete deterioration</td>
</tr>
</tbody>
</table>

Source: Data from Agrawal et al. (2018).

Consists of a review of past performance issues documented with the foundation, inspection of current conditions, and assessment of the environmental conditions surrounding the substructure or foundation being considered for reuse.

Performance issues (such as cracking, rusting, or decay) that have been observed in the past or identified during inspection are likely to cause continuing issues unless the root cause is understood and mitigated. When durability issues are identified, they can be generally tied back to environmental factors, such as the presence of saltwater, fluctuating ground water levels, aggressive soils, or other external factors. Even when past or current issues are not identified, gaining an understanding of these factors can help determine potential durability concerns that have not yet impacted the structure. For belowground elements, it is crucial to understand the environment to which the underground elements are exposed and the potential durability considerations related to this environment. In general, elements that are permanently submerged are less susceptible to corrosion or decay due to the limited availability of oxygen below the water table.

For belowground elements, it is more difficult to perform measurements to aid in the determination of durability parameters, such as chloride penetration in concrete, rebar depth, steel corrosion, or timber pile decay or insect damage. First, it is important to determine the extent that these concerns are expected by considering if the environmental conditions are conducive to deterioration, if the deterioration has been observed, and how feasible performing an investigation on these elements will be. Many deterioration modes will primarily impact belowground elements that are not above the long-term water table. Location of the water table and examination of the portions above that (e.g., through test pits) can provide valuable information on the durability of the pile.

When issues have been identified, field investigations can be performed to ascertain the seriousness of the issue, and whether reuse is feasible and which repair technologies might be required. If the identified issues cannot be completely controlled, service life prediction may be necessary. Generally, this step can be avoided if elements are found to not be susceptible to typical durability concerns, or if corrective action has been taken to rectify those concerns.

Capacity Assessment

Existing foundations have been subjected to loading over their initial service life and therefore have a proven history of performance. However, the original design capacity of the foundation may be unknown, drawings documenting the foundation geometry may not be available, codes may have changed since the original construction, or there may be additional loading applied to the new foundation (from construction loads, additional superstructure loads, or new code requirements). These new loads may require evaluation of the structural capacity of foundation elements, the geotechnical capacity of the foundation system, or both. In addition, existing piers in bodies of water may be subjected to scour that can impose additional loading and create stability issues.

In general, the major difference between the capacity evaluation of a new design and the evaluation of an existing foundation or substructure system is that in situ testing can be used to confirm the adequacy of the existing design. Rather than using design material strengths, in situ testing can be performed to use accurate constructed material strengths. Additional testing can be performed on excavated piles, shafts, or footings to confirm their in situ load capacity and performance curves. Obtaining the in situ properties and performing more advanced analysis than was available during a pier’s original construction can help identify significant reserve capacity in existing structures. This reserve capacity may allow for increased loading on foundations in excess of their original design capacity and previous loading.
Foundation Strengthening

Agrawal et al. (2018) discussed various strengthening measures that are available for Option 4 bridges where greater capacity is required. Strengthening measures can include strengthening of aboveground elements, installation of additional belowground elements, and ground improvement. Scour countermeasure protection can be used to ensure the soil providing resistance is not lost during an extreme flood. Repair technologies for steel elements generally consist of encasement with concrete, installation of cathodic protection, application or reapplication of paint or coatings, or removal and replacement of subpar members. Repair technologies available for timber elements include concrete encasement, PVC wrapping (to inhibit further decay), FRP wrapping (to strengthen and inhibit further decay), grout or epoxy injection (to fill in internal decay), or posting or splicing in new elements to replace areas of decay. Reinforced concrete is the predominant material found in aboveground substructure elements (e.g., piers, columns, abutments) and presents a number of potential issues and repair solutions, as shown in Table 4.

The addition of new geotechnical elements can allow for a wider bridge deck and additional geotechnical and structural capacity. Available technologies for the addition of new elements include micropiles, jacked piles, driven piles, drilled shafts, continuous flight auger (CFA) piles, and tiebacks or soil nailing. In practice, the addition of micropiles and drilled shafts is most commonly observed because they produce very little soil displacement and ground vibrations. These technologies are frequently deployed while the original bridge remains in service.

When existing foundations are suitable for reuse, but issues with the surrounding soil exist, employment of ground improvement technologies can enable reuse. A selection of ground improvement technologies, along with a list of potential uses and how the technology is deployed, are shown in Table 5 Agrawal et al. (2018).

Fig. 5. Wireline logging from Willow Valley Bridge.
When analyzing a bridge replacement project where foundation reuse is considered, innovative bridge deck solutions can become much more viable. These solutions that generally revolve around lowering the weight of the bridge deck may actually increase the cost of the bridge deck, preventing them from being considered during normal foundation construction. When employed to limit dead loads on the foundation and enable reuse, the increased deck cost can be more than offset by the reduced necessity for installation or repair of foundation elements. One of the most commonly employed technologies is the use of lightweight concrete. This technology was employed by the Virginia DOT (VDOT) during the Interstate 95 (I-95) corridor bridge replacement to lower foundation loading by up to 7%. More innovative technologies include the use of lightweight materials to construct decks rather than concrete. Gangarao et al. (2007) described the use of honeycomb FRP decks when replacing short 2-span bridges. By drastically lowering the weight of the deck, the replacement superstructure could be a single span, eliminating the need for the center pier. While the case studies discussed by Gangarao et al. (2007) involved new foundation elements, this approach can be adapted to reduce loading on reused foundation elements.

### Table 4. Strengthening and repair options for concrete elements

<table>
<thead>
<tr>
<th>Category</th>
<th>Identified issue</th>
<th>Strengthening measures available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrity issues</td>
<td>Concrete damage</td>
<td>Replacement of impacted concrete</td>
</tr>
<tr>
<td></td>
<td>Alkali silica reactivity (ASR), delayed ettringite formation (DEF)</td>
<td>Removal and replacement of impacted concrete, replacement of ASR- or DEF-impacted members</td>
</tr>
<tr>
<td></td>
<td>Corroded reinforcement (loss of rebar area)</td>
<td>Removal and replacement of cover concrete with new rebar, doweling, external rebar, FRP wrapping</td>
</tr>
<tr>
<td>Durability issues</td>
<td>Chloride ingress</td>
<td>Removal and replacement of affected concrete, cathodic protection, electrochemical extraction (ECE), expansion joint elimination</td>
</tr>
<tr>
<td></td>
<td>Spalling and delamination</td>
<td>Patching of spalls, galvanic anodes to prevent corrosion, FRP wrapping, addressing primary issue causing spalling</td>
</tr>
<tr>
<td></td>
<td>Freeze-thaw</td>
<td>Removal and replacement of susceptible concrete, wrapping of susceptible concrete with moisture barriers</td>
</tr>
<tr>
<td></td>
<td>Carbonation</td>
<td>Removal and replacement of carbonated concrete, wrapping with moisture barriers, cathodic protection</td>
</tr>
<tr>
<td>Capacity issues</td>
<td>Increased loads</td>
<td>Addition of new elements, encasement of existing concrete sections, addition of external reinforcement cage, FRP wrapping, doweling of additional bars</td>
</tr>
<tr>
<td>Low concrete strength</td>
<td></td>
<td>Replace and add elements, encase with new concrete</td>
</tr>
<tr>
<td>Underreinforcement, detailing issues</td>
<td></td>
<td>Doweling, encasement with additional reinforcement cage, FRP wrapping of low-capacity sections</td>
</tr>
</tbody>
</table>

Source: Data from Agrawal et al. (2018).

### Table 5. Ground improvement technologies for foundation reuse

<table>
<thead>
<tr>
<th>Technique</th>
<th>Uses</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaction grouting</td>
<td>Liquefaction mitigation</td>
<td>Densifies soil by injecting grout volume that displaces original soil; most effective in sandy soils, can cause ground heave and soil displacement near injection</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improve passive resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
<tr>
<td>Jet grouting</td>
<td>Liquefaction mitigation</td>
<td>Soil is jetted out of ground in columns and replaced with grout mixture; can lead to ground displacement when elements are loaded during installation; can be used on sandy and fine-grained soils</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
<tr>
<td>Permeation grouting</td>
<td>Liquefaction mitigation</td>
<td>Grout is injected into soil and allowed to permeate into the void space of soil to improve soil performance; most effective on cohesionless soils</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
<tr>
<td>Soil mixing</td>
<td>Liquefaction mitigation</td>
<td>Rotary tool advanced as grout injected into ground; results in a column of mixed soil and grout with improved properties</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improve passive resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decrease active earth pressure</td>
<td></td>
</tr>
<tr>
<td>Stone columns</td>
<td>Liquefaction mitigation</td>
<td>Provides some lateral stability to soil and some compaction during installation; can allow for excess pore pressures to dissipate; some methods of installation densify the surrounding soil to increase stiffness and reduce settlements</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil densification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
<tr>
<td>Dynamic compaction</td>
<td>Liquefaction mitigation</td>
<td>Densifies soils by repeatedly dropping large weight from crane; improves soil properties where applied</td>
</tr>
<tr>
<td></td>
<td>Bearing capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Settlement reduction</td>
<td></td>
</tr>
</tbody>
</table>

Source: Data from Agrawal et al. (2018).
Foundation Reuse Case Histories

As part of *Foundation Reuse for Highway Bridges* (Agrawal et al. 2018), various case studies were compiled where existing foundations were investigated for reuse. All but one of the case studies considered were Option 3 or 4. The Hurricane Deck Bridge, included in this paper, was investigated for possible reuse, but ultimately was replaced with a new bridge on a new alignment. Two projects, the I-95 corridor in Virginia and the Interstate 93 (I-93) corridor in Massachusetts, extensively reused foundation in kind, where minimal subsurface investigation and evaluation was performed, and loading on the foundations was lowered or maintained at present levels. Three other ABC case studies from that report are discussed in this paper.

**Hurricane Deck Bridge Replacement, Missouri: Option 1**

The Hurricane Deck Bridge was a 5-span under-truss bridge spanning the Lake of the Ozarks in Camden County, Missouri (Axtell et al. 2014). There were four center piers consisting of pneumatic caissons that were believed to bear directly on bedrock. The bridge was originally opened in the early 1930s, and the deck and truss elements required replacement. Since the foundation elements appeared to be in good shape, the bridge owner, Missouri DOT (MoDOT), performed an investigation on the existing foundation elements to assess the feasibility of their reuse for a new superstructure.

The existing caissons were primarily investigated using vertical borings taken from the deck surface. At least two holes were drilled into each caisson with core barrels to allow for examination core recovery, rock quality designation (RQD), testing of removed samples, downhole wireline logging with an acoustic televiwer, and cross-hole sonic logging (CSL) between the completed holes. The CSL performed on these foundations was of limited value, believed to be due to the large spacings between core holes (Axtell et al. 2014). The tests did not identify any major issues with the pier; however, the winning bid was an alternative technical concept (ATC) that involved construction of a new bridge parallel to the existing alignment (Option 1). This proposal increased the number of piers in the lake from four to seven, allowing the superstructure to be a steel girder bridge rather than a delta truss. The winning proposal was 1% cheaper than the cheapest bid that reused the existing foundations. While the Option 1 alternative was ultimately chosen for this project, the reuse (Option 3) alternatives were of similar economic value but may have provided additional benefits such as lower material usage, longer span openings, and maintaining historical appearance.

**I-93 and I-95 Corridor Replacements, Massachusetts and Virginia**

The Fast 14 I-93 replacement project in Medford, Massachusetts (Moran 2012; Jalinoos et al. 2016) and the I-95 corridor replacement in Richmond, Virginia (LeGrand 2015; Jalinoos et al. 2016) are important examples of how foundation reuse can enable and enhance ABC project delivery. Both projects consisted of multiple bridges on busy interstates that could not be closed or rerouted for any substantial amount of time and could not be closed during commute hours. Both projects were delivered using prefabricated superstructure units placed on the existing concrete piers and abutments during weekend or nighttime closures. For the I-93 replacement projects, the substructure portions were in good shape and required only minor patching and repairs. For I-95, a combination of patching of spalls, cathodic protection with an aluminum–zinc–indium galvanic anode, removal of expansion joints over piers, and electrochemical extraction (ECE) were used to provide additional service life to the piers (Sharp 2016).

While the foundations varied across the 25 bridges in these projects, they generally consisted of drilled shafts supported by bedrock. Since the primary source of damage to the piers was due to deicing runoff, and little to no damage was observed near the ground surface, no major investigation was documented into the health and design life of the belowground elements of the foundation. In addition, through use of lightweight concrete, the dead loads on the foundations were reduced for many of the bridges.

**Huey P. Long Bridge, Louisiana: Option 4**

The Huey P. Long Bridge is a combined rail and highway cantilever truss bridge that crosses the Mississippi River in Jefferson Parish, Louisiana (Modjeski and Masters, Inc. 2013). Originally built in 1935, the four truss spans of the bridge cover a combined distance of approximately 682 m (2,238 ft), with the longest span having a length of 241 m (790 ft) and a clearance over the river of 46.6 m (153 ft). The original superstructure consisted of a pair of rail tracks in the center of the bridge, between the distinctive delta trusses. US Route 90 straddled the exterior of the trusses, with two lanes on either side. The highways lacked shoulders, had narrow 2.7 m (9 ft) wide lanes, and had been operating at capacity for a number of years. To address these issues, the bridge was widened using parallel trusses along the outside of the highway travel lanes to support a wider deck with higher loading. To accommodate the additional width of the bridge deck, a steel W-frame (Fig. 6) was constructed on the upper portion of each pier to transfer the loads to the lower portion, which was encased in additional concrete. The widened superstructure and supporting elements increased the dead weight of the bridge, imposing additional loading on the main-span piers and supporting foundations.

The five main-span piers that supported the truss consisted of twin concrete columns founded on open-dredged caissons, with four in the river and the fifth on land immediately adjacent to the river. The caissons were originally designed to be terminated in a dense sand layer approximately 52 m (170 ft) below the river surface and approximately 15 m (50 ft) below the mud line of the deepest part of the river. Geotechnical analysis from the 1930s had estimated that the bearing capacity of this layer was 0.53 MPa (5.5 t/ft²) and that approximately 8.8–12.7 cm (3.5–5 in.) of settlement could be expected from the original bridge loading, which ranged from 0.17 MPa

![Fig. 6. Huey P. Long Bridge with widened superstructure. (Reprinted from Agrawal et al. 2018.)](image-url)
(1.4 t/ft²) to 0.34 MPa (2.8 t/ft²), depending on the pier. Settlement had been monitored from construction until 1990, with settlement in the range of the predictions measured by 1940 and no additional settlement measured after 1940. An investigation was conducted to assess the strength of the in situ concrete and to ensure the foundations would have enough additional bearing capacity to resist the new loading without excessive additional settlement.

Borings were conducted in close proximity to the existing foundations to identify the soil stratigraphy and locate the bottom of the existing caissons. Standard penetration testing (SPT) was performed and undisturbed samples were taken for laboratory testing. New analysis estimated that the bearing capacity of the foundation was substantially higher than the original 0.53 MPa (5.5 t/ft²) and that additional proposed loading would lead to an additional 2.5–3.8 cm (1–1.5 in.) of settlement. No additional settlement was observed during construction monitoring. The concrete in the existing pier columns was tested and found to be of significantly higher strength than the design. The 28-day strengths from the original test data were extrapolated to present-day strengths following findings by the American Concrete Institute (1992) and Neville (1995), and these strengths were used in the final design of the new encased piers. Diving inspections and sonar imaging were performed to evaluate the condition of the below-water portions of the pier and the extent of scour. The aboveground portions of the piers appeared to be intact and scour around the piers of up to 7.9 m (26 ft) deep was observed. These scour holes had not undermined the foundation and the design did not rely on soil resistance from scoured or scour-prone depths. The results of one of the sonar imaging surveys showing scour is shown in Fig. 7.

**Milton Madison Bridge, Indiana and Kentucky: Option 4**

The Milton Madison Bridge (Fig. 8) is a major crossing of the Ohio River between Indiana and Kentucky that was originally constructed in 1928 (Jalinoos 2015; Jalinoos et al. 2016; Tiberio 2015; Ligozio and Villalobos-Chapa 2009). The bridge is a signature 5-span through truss that has significant historical value and overlooks a historical district in neighboring Madison, Indiana. In addition, closure of the crossing would have resulted in an approximate 80-km (50-mi) detour to cross the Ohio River. The original superstructure was in poor condition and had no shoulders and narrow lanes that were insufficient by modern standards. To address these issues, the superstructure was replaced using a slide-in-place deck that had 3.7 m (12 ft) wide traffic lanes, 2.4 m (8 ft) wide shoulders on either side, and a 1.5 m (5 ft) wide sidewalk. Two replacement (Option 1) alternatives were considered alongside a strengthening and reuse (Option 4) alternative. The Option 4 alternative that reused four of the original piers was chosen because it presented an approximate $50 million cost savings (Tiberio 2015).

The substructure consisted of four piers founded on pneumatic caissons in the river and five approach piers. The existing piers showed signs of aging, including cracking on the pier faces, de-

![Fig. 7.](image1) (a) Above-water image; and (b) sonar image of a bridge pier. (Reprinted from Agrawal et al. 2018.)

![Fig. 8.](image2) Milton Madison Bridge prior to renovation. (Reprinted from Agrawal et al. 2018.)
laminated sections, lift lines from the original construction, and areas of paste erosion. Piers 4 and 5 (the leftmost piers in Fig. 8) had been exposed to deicing chemical runoff and were considered to be in too poor of shape to be salvageable. The remaining piers had various uncertainties, such as rebar location and depth, concrete strength, concrete integrity and deterioration, and chloride penetration. Design plans showed the foundations consisted of unreinforced pneumatic caissons that extended to bedrock well below the riverbed.

A thorough investigation was carried out to assess the integrity of the original piers and underlying caissons. This program included vertical core holes, sampling (pier and caisson concrete, underlying soil) and wireline logging performed from the bridge deck, and sample extraction from the bridge faces. The primary concerns during the investigation included the compressive strength of the pier and caisson concrete, the pier reinforcement condition, and the extent of chloride penetration in the pier sides. An overview of the concrete testing performed at the Milton Madison Bridge is shown in Table 6.

After the test program was completed, it was determined that four piers (Piers 6–9) were salvageable, although they required encasement in 61 cm (24 in.) of new high-performance concrete (HPC) to achieve a design life of 75 years. The new concrete was reinforced with epoxy-coated rebar and designed to carry all new loading.

A capacity assessment was performed on the piers using properties obtained during testing and information from design drawings. Finite-element analysis showed that the unreinforced portions could be subjected to tensile stresses under wind loading.

<table>
<thead>
<tr>
<th>Test performed</th>
<th>Issues evaluated with testing</th>
<th>Extent of testing</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-penetrating radar (GPR)</td>
<td>Cover depth, rebar layout</td>
<td>135 scans performed along three reused piers and one pier not reused</td>
<td>Drilling locations were chosen to avoid rebar; GPR survey confirmed very low reinforcement ratio</td>
</tr>
<tr>
<td>Impulse response</td>
<td>Extent of delamination, check for indications of honeycombing and subsurface voids</td>
<td>Performed along three reused piers and one pier not reused</td>
<td>Area of higher reflectivity corresponded to delaminated areas of concrete</td>
</tr>
<tr>
<td>Down-hole camera in core hole</td>
<td>Integrity of interior concrete</td>
<td>One core on each of four salvageable piers</td>
<td>No significant voids observed, ineffective below water line</td>
</tr>
<tr>
<td>Single-hole sonic logging (SSL)</td>
<td>Determine if voids or defects are present in pier</td>
<td>One core on each of four salvageable piers</td>
<td>Anomalies reported just above caisson–soil interface, few other minor anomalies</td>
</tr>
<tr>
<td>Petrography</td>
<td>Mix properties; damage from freeze-thaw, erosion, alkali silica reactivity (ASR), carbonation penetration</td>
<td>Performed on 15 core samples, some extracted from exterior face, some from vertical coring through center of pier</td>
<td>Mix properties verified, minimal freeze-thaw or ASR noted, little carbonation penetration</td>
</tr>
<tr>
<td>Compression tests</td>
<td>Compressive strength</td>
<td>58 compression tests; 54 on 5-cm (2-in.) cores, four on 10-cm (4-in.) cores</td>
<td>Compressive strength taken as 1.5 standard deviations below average of the 54 tests on 5-cm (2-in.) cores</td>
</tr>
<tr>
<td>Modulus tests</td>
<td>Modulus of elasticity for concrete</td>
<td>Performed on two 10 cm (4 in.) diameter cores, also taken from concrete strength found from compression testing</td>
<td>Modulus used was from strength-based calculations</td>
</tr>
<tr>
<td>Chloride testing</td>
<td>Level of chloride penetration</td>
<td>Total of 138 powder samples extracted for five different piers; four samples taken at each location at 2.5-cm (1-in.) intervals [up to 11.4 cm (4.5 in.) deep]</td>
<td>Four of five piers did not have significant chloride exposure, even at surface; one pier had chloride levels higher than threshold (0.3% by weight) at rebar level</td>
</tr>
</tbody>
</table>

**Fig. 9.** (a) Coring of caisson concrete from inside of cofferdam; and (b) insertion of reinforcement. (Reprinted from Agrawal et al. 2018.)
acting on the superstructure. To carry these stresses, epoxy-coated steel was doweled into the pneumatic caissons as tensile reinforcement. Drilling was performed through the existing foundation after installation of a cofferdam [Fig. 9(a)] and epoxy-coated rebar [Fig. 9(b)] in the completed holes.

Additional geotechnical stability (due to overturning) issues were found during the capacity assessment due primarily to large design scour depth of up to 12.5 m (41.1 ft) deep. When the foundation was analyzed without the loss of the scourable soil, overturning was not an issue. To prevent the loss of this soil, scour prevention measures in the form of riprap and geotextiles were installed alongside the foundation. The evaluation and improvement performed on the pneumatic caissons allowed their reuse without the need for new foundation elements.

**Mississagi River Bridge, Ontario, Canada: Option 4**

The Mississagi River Bridge in Iron Bridge, Ontario, Canada, carries a provincial highway over the only major crossing of the Mississagi River for dozens of miles in either direction (Li et al. 2014). Originally constructed in 1943, the bridge deck suffered from corrosion and deterioration and was in generally poor condition. Since acquisition of the adjacent ROW was not possible, a plan that maintained the existing alignment while reusing the existing piers was necessary. These piers were constructed by driving steel sheet piling into the river bed, excavating soil to the desired bearing surface, and filling the cofferdam with concrete. It was believed that all piers were founded directly on bedrock. Vertical core holes were drilled through the piers into the underlying soil and bedrock, finding that three of the original piers had been founded on soil instead of bedrock. Deterioration of the steel sheet piling was observed through visual and ultrasonic inspection; the existing scour was measured through visual observations. In some spots, the existing scour was beneath the footing bottom, and there was concern that the soil-supported piers would become unstable as the cofferdams continued to deteriorate. The foundation was underpinned using micropiles drilled through the existing footings and the underlying soil to bedrock. This approach allowed underpinning of the existing foundation without complete closure of the bridge because micropiles were installed from the existing bridge deck (Fig. 10).

The new micropiles were connected to the existing bridge using a new pile cap poured around the existing pier wall. Steel rails were used as compression struts that connected a pair of micropiles on either side of the pier to the new pile caps and old piers. A threaded bar was used as a tension tie below the tops of the micropiles to prevent the new pile cap from separating from the pier. The new cap was poured in multiple sections and continued to the top so that the existing pier was encased. The new piers were provided with ice nosing to prevent the buildup of ice and associated loading. Riprap (loose stones) large enough to resist scour at the expected flood velocities was placed around the piers to fill in old scour and prevent new scour from eroding the lateral resistance of the pier.

**Summary of Case Studies**

From the case studies documented in this paper, it is clear there is a wide range of investigation that can be and is performed on current bridges. For the Huey P. Long Bridge, significant additional capacity was identified during original construction that was confirmed through testing and analysis. Updated projections of the settlement expected to occur due to increased dead loading were estimated to ensure this capacity could be utilized without excessive settlement. For the Milton Madison Bridge, additional capacity was required due to changes in dead load and updated codes. Rebar was doweled into the existing caisson concrete to provide sufficient structural capacity, and scour protection was added to preserve the geotechnical capacity against possible future scour. The I-95 and I-93 corridors provide examples of bridges where there was minimal concern about the capacity or integrity of the belowground elements and the reuse of these foundations primarily involved repairing substructure damage and limiting loading to equal to or lower than the original loading.

Ultimately, the decision on whether or not to reuse a foundation and the investigation that needs to be performed depends heavily on engineering judgment. The risks posed by reusing a foundation can be mitigated by developing a systematic procedure that identifies which quantities need to be assessed and the appropriate procedures. Developing a procedure that uses readily available information to identify which testing is needed can help make foundation reuse a more economical option.

**Conclusions**

The reuse of existing foundations during ABC projects presents many possible benefits in terms of direct cost savings, faster construction, lower user impacts, and reduced environmental impacts. Still, reuse can present new challenges to designers and bridge owners that complicate the risk analysis and decision-making process. Considering these challenges can add to the cost and complexity of a project, but following a systematic decision-making process that identifies needed information and devises a focused testing program can help mitigate these costs. From the case studies presented, a wide range of investigation, strengthening, modeling, and assessment has been performed based on engineering judgment and the requirements of the project.

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References


Li, E., S. Morozzevych, and C. Lo. 2014. “Underpinning of existing foundations of a major river crossing using micropiles in Ontario, Canada.” In *Proc., 9th Int. Conf. on Short and Medium Span Bridges*. Montréal: Canadian Society for Civil Engineering.


